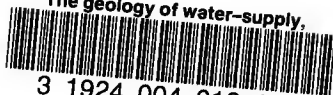




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THE GEOLOGY OF WATER-SUPPLY

ARNOLD'S GEOLOGICAL SERIES

General Editor : DR. J. E. MARR, F.R.S.

THE GEOLOGY OF WATER-SUPPLY

BY

HORACE B. WOODWARD, F.R.S., F.G.S.

LONDON
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1910

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EDITOR'S PREFACE

OUR great educational centres have grasped the importance of geology in its economic aspect, and the books of this series are designed in the first place for students of economic geology. It is believed, however, that they will be found useful to the student of general geology, and also to miners, surveyors, and others who are concerned with the practical applications of the science.

'The Geology of Coal and Coal-Mining,' by Dr. Walcot Gibson, and 'The Geology of Ore Deposits,' by Messrs. H. H. Thomas and D. A. MacAlister, have already appeared. Other volumes will follow.

The author of the present work, late Assistant Director of the Geological Survey of England and Wales, has long been an authority on water-supply, having had many years' practical acquaintance with the principal water-bearing strata of the island, and with the requirements of engineers and well-sinkers in connection with the subject.

J. E. MARR.

AUTHOR'S PREFACE

IN considering the best means of obtaining an adequate supply of potable water, a knowledge of the geological structure of the ground and of the lithological characters of the rock-formations is necessary. It is requisite in many cases to know, as far as possible, the extent and capacity of the water-bearing strata; it is important in all cases to ascertain whether the proposed supply is liable in any way to contamination.

The geologist, therefore, is usually called upon, in the first instance, to advise on the prospects of a good supply of water, with especial reference to the nature of the gathering ground, and the sources of the springs, streams, or underground supply, which it is proposed to utilize.

Like other subjects, that of water-supply has an extensive literature; but, so far as the writer is aware, the geological aspects have not been given prominence hitherto in a separate volume. In the text and bibliography acknowledgment is made of certain original publications to which the writer is particularly indebted, and references are given to some further sources of information on the engineering and other branches of the subject. While the results of detailed researches carried out in the United States on rain and rivers, and the underground circulation of water, have been most helpful, no one attempting to deal with water-supply in connection with the geological structure of England and Wales could do so justly without expressing his great obligations to the published works of Mr. William Whitaker, F.R.S.

HORACE B. WOODWARD.

CROYDON, 1910.

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THE GEOLOGY OF WATER-SUPPLY

CHAPTER I INTRODUCTION

THE means of obtaining supplies of water for domestic and municipal purposes, also for industrial establishments of many kinds, is a subject that affects both individuals and communities. In selecting a site for building a cottage or mansion, outside the district of a water-company, the question of an appropriate water-supply is of primary importance. In villages where the wells have become contaminated or liable to pollution, in towns and cities where the growth of population demands increased supplies, in new settlements before mining operations, irrigation works, and factories, can be established, the subject of water requires urgent consideration. So also in military camps, whether occupied during manœuvres or in actual warfare, the question of water is no less vital.

✓ The sources of water-supply depend almost wholly on the rainfall, and the consequent springs, rivers, and lakes; and on the geological structure which enables certain rocks to store large supplies of the rain that has percolated through the soil. As these factors are

subject to extreme variation, so the problem of obtaining wholesome and adequate supplies may be either simple or fraught with great difficulty and uncertainty.

Fresh water is required in all regions from the tropics to the poles, and at different elevations, so that recourse must be had in some situations to the melting of snow or glacier-ice, to natural water-holes in arid regions, or to the sinking of wells along a dry river-course, and to distillation of sea-water, mostly on the ocean, but sometimes on land.

In primitive times, springs, brooks, and rivers, pools and lakes, yielded the wanted supplies, and the earliest settlements were made in places where water was freely obtained. Migration, however, was necessary sometimes on account of drought, more often from the experience gained by the inevitable pollution of the soil; and change was readily effected so long as the population was scanty and the land was free to all comers.

The fortifications that became necessary with the growth of civilization required supplies of water on elevated situations, notably on the Chalk and other limestone hills in this country. As often seen on the floor of a chalk-pit, the powdery material, like whiting, will hold up water when moist, and during the construction of earthworks, as remarked by Mr. F. J. Bennett,¹ it may have been noticed that trenches held water for a time after heavy rain. Thus, the notion of storing water may have led to the construction of ponds, some of which, known as Dew-ponds, are considered to date back to the Neolithic period.²

¹ *Proc. Geol. Assoc.*, x., 1888, p. 376.

² 'Neolithic Dew-ponds and Cattle-ways,' by A. J. and G. Hubbard, 1905.

In prehistoric times in Britain, the shallow excavations made for pit-dwellings, the shafts dug for the purpose of extracting flints from the Chalk or for Dene-holes, no doubt proved in places how water could be obtained beneath the surface of the earth; and wells were constructed during the Roman occupation on the Chalk downs of Cranborne Chase on the borders of Wiltshire and Dorset, as made known by Pitt-Rivers, and at Leckhampton, one of the ancient camps on the Cotteswold Hills. Pitt-Rivers was of opinion that the water-level in the Chalk of Cranborne was about 33 feet higher than it is now, owing to greater rainfall. One Roman well was 188 feet deep.¹

Well-sinking and boring for water, aqueducts for household supplies and irrigation, date back in other parts of the world to very early times, as in China and India. The irrigation-works constructed in Babylonia for agricultural purposes, and to mitigate the floods, are considered to be at least as old as 2000 B.C., while aqueducts, with in some instances tunnels through hills, were made by Greeks and Romans in ancient days to convey water from springs, rivers, and lakes, for household and other purposes.² Remains of Roman aqueducts have been found in Durham.

That there are considerable bodies of water under the earth was manifest by certain deep-seated springs or flowing wells, some, like the thermal waters of Bath, coming naturally to the surface. Others with natural exits probably existed in certain of the Egyptian oases, but, as elsewhere remarked, these underground sources were developed at an early date by the Romans.

¹ 'Excavations in Cranborne Chase,' vol. i., 1887, p. 27.

² See address by Mansergh, 1900.

In the old province of Artois (Artesium), in the north-east of France, wells that mostly derive their water from the Chalk have long been known to yield supplies, which, being pent up beneath impervious strata, rose in the shafts or bore-holes to various elevations, and sometimes overflowed. The oldest well of this nature in Europe is said to have been made A.D. 1126.

Augsburg, to the north-west of Munich, in Bavaria, was one of the first cities in Europe to have a public water-supply. The system was described by Montaigne in his 'Travels in Italy' in 1580 and 1581.¹ The water was conveyed from a spring by a wooden aqueduct, and the current 'turns a number of water-wheels attached to pumps, which, by means of two leaden pipes, raise the water of a spring, which rises in a hollow, to the top of a tower some 50 feet in height. On the top of this tower the water is poured into a great stone cistern, and from this cistern it runs down through divers pipes, and is distributed all over the city, which in consequence is abundantly supplied with fountains.'

During the Middle Ages in Britain there were a certain number of public wells, springs with tanks and conduits, and water was distributed by skeels or buckets and by water-carts. The City of London was first supplied from springs at Tyburn in 1236. Tiverton had a town supply as early as 1240, Bath in 1500, Northampton about the same date or earlier, and Plymouth soon after 1585; but organized water-works were not generally established in the large towns before the seventeenth century.

In the permanent settlements in this country, whether town or village, many of the shallow wells

¹ See edition by W. G. Waters, 1903, vol. i., p. 135.

have been abandoned, owing to pollution from defective drainage and other sources, and cases continually arise which necessitate deeper wells or distant supplies. In many an old castle and in manor-houses the well was inside the inhabited portion of the enclosure, sometimes in the kitchen, and such positions would not now be regarded as sanitary. The old well in the keep of Norwich Castle is 115 feet deep, and still holds water.

Borings in England were made during the eighteenth century in the London area, and flowing (artesian) water was tapped in many low-lying areas beneath the thick mass of London Clay.

The underground water, derived from the rainfall on the Chalk tracts that extend to the Chiltern Hills and Dunstable Downs on the north, and to the North Downs and bordering slopes on the south of London, has been so extensively drawn upon that fears are entertained of the ultimate failure of the water to meet the demand.

The method of increasing supplies from wells by means of tunnels or collecting galleries was put in practice by the Romans during their occupation of Egypt, and the system advocated in England by William Smith in 1817 has been extensively adopted in this country. It is successful in many places where the underground supply is not drained by too many wells.

If civilization has to some extent brought trouble and expense in providing adequate supplies of water in densely populated places, yet the health of the inhabitants in many towns and country places has been greatly improved.

In London the death-rate in the seventeenth century was nearly 80 per thousand, in the eighteenth century about 50, and at the close of the nineteenth century about 20 per thousand.

The problem of providing sufficient supplies for all parts of the British Islands, and especially for the manufacturing towns that rapidly increase in size, has caused some anxiety. The question resolves itself into one of the conservation of the water. If we take the estimate of the annual rainfall of the world, as given by Professor W. J. Sollas, we may reckon upon an amount equal to more than 26,000 cubic miles; nevertheless, anxiety is felt lest we get into the state supposed to exist on the planet Mars, with its so-called snow-caps and canal-system, as it is conjectured that 'the one great aim and object of the whole of the intelligent minds on Mars is concentrated on making the utmost use of the slowly diminishing water-supply.'¹

Dr. H. R. Mill, in endeavouring to relieve our minds, stated in 1909 that 'A rainfall of only 30 inches over one-tenth of the land surface of the British Isles would yield, could it be all utilized, a supply of 350 gallons per head per day for the whole present population of the country.'²

Much attention, indeed, has been given to the desirability and ultimate necessity of public control over all the main sources of water-supply in the British Islands, not merely for purposes of conserving the water, much of which is lost during times of flood, but

¹ See review in *Nature*, April 22, 1909, of 'Mars as the Abode of Life,' by Professor Percival Lowell; also Lowell, *Nature*, August 29, 1907.

² *Journ. Statist. Soc.*, lxxii., 1909, p. 294.

also of protecting the gathering grounds from contamination. On this subject further remarks will be made.

In considering the question of important local supplies of water, recourse must be had to—(1) the *Meteorologist*, whose information on rainfall is for the most part published; (2) the *Geologist*, who would report on the geological structure of the gathering ground or any proposed site for a reservoir, on the depth at which underground supplies are to be expected, and on the possible sources of contamination; (3) the *Engineer*, who would deal with the gauging of springs and streams, with the amount of the rainfall that would be available from the surface or underground, who would determine the relative advantages of gravitation and pumping schemes, and carry out or superintend the works, whether well, boring, reservoir, or river supply; (4) the *Well-sinker* and borer, who would carry out the work of digging and drilling; and (5) the *Analyst*, who would report on the chemical and bacteriological character of the water.

In small undertakings for the supply of a cottage or single house, the advice of an experienced well-sinker may in many cases be sufficient, and if information be given by the Medical Officer of Health as to the general sanitary conditions of the district, so much the better. In all large undertakings the *Engineer* naturally takes supreme command.

CHAPTER II

GENERAL REMARKS ON RAINFALL AND ATMOSPHERIC IMPURITIES

As the sources of water-supply depend almost wholly on the rainfall, the consideration of this subject is of first importance both for surface and underground waters.

Rainfall is taken to include rain, hail, sleet, snow, and dew, and the following are the essential points with which our present inquiry is concerned :

1. The mean annual rainfall over a particular area.
2. The amount that runs directly off the surface by streams—the ‘run-off,’ as it is commonly termed.
3. The amount lost through evaporation, and absorption by vegetation.
4. The amount that percolates through the soil into the permeable and fissured strata, the overflow from which issues in the form of springs and seepage.

All these points are subject to great variation in different areas, according to climatic conditions, physical features, geological structure, and the natural or artificial state of the ground.

The total annual fall of rain on the earth's surface has been reckoned to be sufficient to cover it to a depth of nearly 3 feet ; but while some regions have a superabundance of rain, others are practically waterless.

In Polar regions the annual snowfall represents from 8 to 15 inches of water, on the southern slopes of the Himalayas the rainfall may be as much as 50 feet, and even an amount of 67 feet in one year has been recorded on the eastern coast of the Bay of Bengal. On the other hand, there are vast areas of desert in Northern Africa, Central Asia, Australia, Mexico, and along the coast of Peru, with little or no rainfall, while among the Canary Islands there may be a dearth of rain in some parts for a period of three years.

In considering the subject in reference to water-supply, it is necessary to consult the records that are published or otherwise available; to ascertain whether the rainfall is periodic, irregular, or fairly distributed throughout the year; and to learn as much as possible about the mean annual and monthly amounts, with particulars of any unusual rainy or dry periods.

Localities with a large annual rainfall may have fewer rainy days than those with a moderate rainfall. The amount of rain often varies much within short distances, locally and temporarily, and elsewhere permanently, according to physical conditions. Although hilly and mountainous grounds usually receive more rain than the low lands, much depends on the distance from the sea of the higher tracts. In many places rather more rain falls on the low ground than at somewhat higher elevations, and more falls on the land than on the sea.

Sir A. R. Binnie (1887) mentions a fall of $23\frac{1}{2}$ inches of rain in twenty-four hours at Madras, and of 12 inches in three hours at Calcutta. In Jamaica in November, 1909, torrential rains occurred for several days with an average fall of 10 inches, and on one day 13 inches.

In the British Islands a fall of rather more than

6 inches of rain has locally been recorded in one day ; but, as remarked by G. J. Symons, the extreme amount has not been noted, as 'it is a question of catching and measuring a broken water-spout.'¹ (See p. 317.)

A 'cloud-burst' occurred on the borders of Dorset and Devon on December 26, 1886, but the total rainfall registered at the Rousdon Observatory, near Lyme Regis, was 2·65 inches for the day.² One or two inches of rain may fall during a thunderstorm in the course of a few hours.

The heavy rainfall which occurred in the south-east of England during October 24 to 30, 1909, included a total fall, during three days, at Ramsgate of 6 inches, and at Brighton of 5·27 inches ; but at Brighton as much as 3·60 inches fell in the course of one day.

The average annual rainfall in the British Islands is reckoned by Dr. H. R. Mill to be 39·5 inches, but it varies locally from an average of 130 inches at Sty Head Pass, Seathwaite, in Cumberland, to less than 25 inches in the Eastern Counties of England ; while in point of time, in 1872 the total rainfall was 53 inches, in 1887 only 30½ inches, for the British Isles.

In 1908 the largest amount recorded by Dr. Mill was 237·3 inches, at Llyn Llydaw, Snowdon, and the smallest amount 15·6 inches, at Bourne in Lincolnshire.

So uncertain is the rainfall in England that G. J. Symons remarked, in 1867, that no one 'can tell us which is the wettest and which is the driest month.' In the western districts the rainfall is more uniformly distributed, and often less heavy than in tracts with a smaller annual fall. Nevertheless in the Exe Valley there is consider-

¹ 'Modern Meteorology,' 1879, p. 154.

² *Proc. Geol. Assoc.*, xix., 1906, p. 333.

able variation as noted by Dr. Mill; the annual rainfall is nowhere less than 30 inches, and the average is 42, but a wide area on Dartmoor has more than 70 inches.¹

In the Upper Thames Basin, above Oxford, the mean annual rainfall is reckoned at 30 inches, but the amount varies from 19 inches to more than 48 inches. In Suffolk the mean average rainfall, as estimated by Dr. Mill, is 24·5 inches, the maximum (in 1872) was 33·1, the minimum (1870, 1887, and 1901) 18·4, and the average of the driest three years (1900-1902) was 20·8 inches.²

The records of rainfall in the British Isles are sufficiently complete for practical purposes.³ A record of forty years gives a safe average, but in some localities dependence has to be placed on records of less duration.

Dr. Mill has estimated that the annual rainfall of England and Wales, taken at 32 inches, would yield 27,019,632 million gallons of water.

In reckoning the amount of available rainfall, it is customary to take the mean average of the locality or district, and to deduct $\frac{1}{5}$ or $\frac{1}{6}$ as an allowance for three consecutive dry years. Experience has shown that this allowance is necessary in questions of water-supply. Further deductions have to be made for loss by evaporation and absorption, as will be subsequently noted.

It has been estimated that the minimum rainfall in

¹ *Nature*, December 30, 1909, p. 258.

² 'Water-Supply of Suffolk,' *Mcm. Geol. Survey*, 1906, p. 14. Dr. Mill has contributed articles on County Rainfall to the Water-Supply Memoirs published by the Geological Survey. (See Appendix.)

³ See 'Rainfall Tables of the British Islands,' 1866-1890; and 'British Rainfall,' published annually, edited formerly by G. J. Symons, and now by Dr. Mill.

different countries may vary from $\frac{1}{4}$ to $\frac{1}{2}$ of the maximum, and equal about $\frac{2}{3}$ of the average rainfall.

Mr. J. Mansergh (1882) mentioned a drought of more than 500 days that was felt in parts of Northumberland, mainly during 1876, as 560 days elapsed between the date when the water began to go down in the reservoirs of the Newcastle Water Company and the date when they were again being filled. This does not imply that there was no rain at all, but that the amount was comparatively small.

Dr. H. R. Mill, in referring to British rainfall, observes that it has been usual to reserve the words 'absolute drought' for a period of more than fourteen consecutive days without recorded rainfall.¹

Suggestions have been made for the production of rain by artificial means. The matter was thoroughly tested by explosives in the United States in 1892, and no rainfall was produced by the bombardment.²

The composition of rain-water is a matter of some importance. The atmosphere contains small amounts of carbonic acid, nitric acid, sulphuric acid, ammonia, and chloride of sodium, which are brought to the earth by rain. The amounts vary, more especially as regard sulphuric acid and chloride of sodium, which are in greater proportions in the vicinity of large towns and near the sea-coast respectively. The ordinary amount of carbonic acid is reckoned to be about 3 parts per 10,000 parts of air, and of ammonia 0·021 part (in town), and 0·003 part (in country).

Other ingredients occur in the atmosphere and in rain-water to which attention may briefly be directed,

¹ *Nature*, October 28, 1909, p. 517.

² *Ibid.*, December 13, 1900, p. 167.

inasmuch as consideration must be given to them in connection with the direct usage of rain-water for household purposes.

Dust.—It is well established from the observations of Mr. John Aitken and others that the atmosphere everywhere contains a certain amount of dust, which varies in amount according to the atmospheric pressure and wind. It occurs usually in greatest abundance at low levels, but is found on the summit of Ben Nevis and elsewhere at elevations of more than 13,000 feet, and over the ocean.

The term 'dust' is taken to include all minute particles—animal, vegetable, and mineral—that are capable of suspension and transport in the air. It includes micro-organisms, material derived from roads, river-banks, seashores, deserts, and volcanoes, cosmic or meteoric dust, as well as coal-dust and soot. Much of this dust is brought to the surface of the land by rain or snow, but a good deal falls independently.

Volcanic dust, most of which is greyish-white, has been transported to a distance of more than a thousand miles, floating for many weeks, and raised to a height estimated at seventeen miles, in the case of the great eruption of Krakatoa, in the Strait of Sunda, in 1883.

Red rain, or, as it is sometimes called, Blood rain, and red and yellow snow, have been caused by the transport of fine red or yellow sand from the Sahara desert, material spoken of as 'Sirocco dust.' Red rain is also caused by the wind carrying ferruginous material from the dried surfaces of red muddy swamps and salt lakes. In Australia as much as 50 tons to the square mile has been deposited in Victoria, according to estimates

made by Messrs. F. Chapman and H. J. Grayson.¹ Somewhat similar material has been derived from the borders of the Red River below Camborne, where red mud or slime (largely peroxide of iron) is carried down from the tin stream-works, and liable when dry to be wind-drifted and brought down as red rain.²

Snow that is rose-coloured, pink, or red, and sometimes green, is caused by the presence of minute algæ, and has been observed on the snow-clad mountains of New Zealand as well as in Polar regions.

Black rain, due to other causes, has been recorded. This is sometimes produced by forest fires and other great conflagrations; probably more often by the soot and coal-dust carried away in clouds from manufacturing and coal-mining districts, such as the South Wales coal-field.³

The influence of dust on fogs is well known, the deposit of moisture on the particles being especially characteristic of 'dry fogs.'

The composition of the fogs in the London district has been studied by Dr. W. J. Russell. The more stable constituents, as deposited on previously washed glass roofs at Kew and Chelsea during a fortnight in February, 1891, yielded over an area of 20 square yards at Kew 30 grammes of deposit, and at Chelsea 40 grammes, the last-named amount being equal to 22 pounds per acre, or 6 tons to the square mile. Analyses showed the following composition per cent. :⁴

¹ *Victorian Nat.*, xx., June, 1903.

² C. Reid, *Nature*, lxxv., 1902, p. 414.

³ *Nature*, March 12, 1908, p. 445.

⁴ *Ibid.*, November 5, 1891, p. 10.

	Chelsea.	Kew.
Carbon	39.0	42.5
Hydrocarbons and organic bases (pyridines, etc.)	14.3	4.8
Sulphuric acid	4.3	4.0
Hydrochloric acid	1.4	0.8
Ammonia	1.4	1.1
Metallic iron, magnetic oxide of iron, and mineral matter (chiefly silica and ferric oxide)	33.8	41.5
Water, not determined (say difference)	5.8	5.3
	100.0	100.0

More recent analyses of snow taken from the roof of the *Lancet* office show the great amount of impurity, and the difference between that on a week-day and on a Sunday :¹

	Tuesday, December 29, 1908.	Sunday, February 28, 1909.
Suspended matter (chiefly soot, coal-dust, and tar)	Grains per Gallon. 30.32	Grains per Gallon. 6.65
Mineral matter in solution	4.20	1.93
Organic matter in solution	7.84	1.57
Free ammonia	0.07	0.05
Organic ammonia	0.01	0.02
Chloride of sodium	1.33	1.27
Sulphuric acid	3.36	trace
Nitric acid	traces	—

¹ *Lancet*, January 2, 1909, p. 49; March 6, p. 702. See also *Nature*, October 14, 1909, p. 468.

From the results of the lesser amount on Sunday, it was calculated that the snowstorm on that day carried to the surface of the County of London about 75 tons of dissolved matter and 142 tons of suspended matter, including about 25 tons of common salt, 1 ton of ammonia, and 100 tons of coal!

The utilization of rain-water is dealt with in Chapter VII.

CHAPTER III

GENERAL GEOLOGICAL CONSIDERATIONS

BEFORE considering the dispersion of the rainfall on the surface and underground, it is desirable to make some general remarks on geology that may be applicable to any portions of the earth's surface.

The term *rocks* is applied to all materials, other than true crystalline minerals or mineral species, which enter into the composition of the solid surface or crust of the earth. These materials are hard and soft, stony or earthy, loose or compact—such as limestone and marl, slate, shale and clay, sand, sandstone, gravel and conglomerate; and they include the crystalline rocks made up of aggregates of minerals, such as the various granites and greenstones, and the schistose metamorphic rocks, gneiss, mica-schist, etc.

The **water-bearing rocks**, or those which yield supplies of water, are of two kinds:

1. The porous and permeable, which hold water more or less freely throughout their mass.
2. Those which are practically impervious in mass, but hold water in joints, caverns, fissures, and other cavities, or in shattered or decomposed superficial portions.

1. *Porous and Permeable.*

Sand.
 Soft sandstone.
 Gravel.
 Loose breccia.
 Sandy limestones.
 Chalk.
 Oolite.
 Marlstone.
 Dolomite or Magnesian Limestone.
 Brown ironstone-beds.
 Decomposed earthy portions of Granite, Greenstone, and veins in Metamorphic rocks.

2. *Holding Water in Joints, Fissures, Caverns, Faults, Shattered Portions, and Other Crevices and Cavities.*

Quartzite.
 Hard siliceous sandstone.
 Grit.
 Conglomerate and pudding-stone.
 Hard limestone and marble.
 Slate.
 Granite.
 Greenstone.
 Gneiss.
 Crystalline schists.

The non-water-bearing rocks are also of two kinds :

1. Those which are absorbent and partially pervious, but do not yield supplies of water.
2. Those which are more or less absorbent, but practically impervious.

1. *Partially Pervious.*

Very fine sand (silica sand).

Sandy loam (brickearth).

2. *Impervious.*

Clay.

Shale.

Marl (calcareous clay).

Clay-loam (brickearth).

Tabular flint and bands of chert.

Slate, where not shattered or jointed.

Schists, ditto.

Granite, ditto.

Greenstone, ditto.

Hard limestone and marble, where not shattered or jointed.

Iron-pan, where not shattered or jointed.

Conglomerate and pudding-stone, where not shattered or jointed.

All rocks, as noted farther on, are more or less porous, but this does not imply that they are pervious or permeable.

Rocks such as those enumerated may be found in all parts of the globe, and at various geological horizons.

These horizons, or stratigraphical positions, mark epochs of time, and are indicated in tables of geological formations.

— **Formations** are made up sometimes of comparatively uniform masses of clay, slate, sandstone, or limestone; sometimes of alternations ^{strata} of limestone and clay, of sandstone and shale. They are essentially based on lithological and stratigraphical characters, and the

limits assigned to them are more or less local for each country or district.

Not only the individual bands of rock, but the formations in general, are subject to gradual and sometimes rapid modifications. More especially are the water-bearing sedimentary formations, the sandy and calcareous strata, liable to somewhat rapid changes in character and thickness, not only when followed abroad, but in different portions of the British Islands, so that different local subdivisions, with distinct names, become necessary.

In Germany, for example, the representatives of the Chalk formation consist largely of sandstones; and the Oolitic limestones of the West of England are represented in Yorkshire mainly by sands and shales.

In regions where the geological structure is but little known, the determination of the age of the formations may not be a matter of great importance, the nature and arrangement of the rocks being the primary consideration.

In countries where the nature and age of the formations are well known, as in Britain, much has yet to be learnt of the underground structure; and the aid of fossils is all-important in determining geological horizons in deep wells and borings, as they may give clues to the thickness of strata to be penetrated, and afford means of deciding whether a boring should or should not be continued to a farther depth.

It would be impossible here to enumerate the species of fossils characteristic of each formation, nor would lists of names unaccompanied by figures be of much service.¹

¹ For figures of characteristic British fossils, see Stanford's 'Geological Atlas of Great Britain and Ireland,' by H. B. Woodward, 2nd edit., 1907.

The identification of the fossils must be left to the geological adviser, or information may be obtained in some public museum.

The broader groups or systems, comprising several geological formations, are arranged under names of universal application; they are chronological, and serve to indicate periods of time irrespective of the lithological characters.

AQUEOUS, SEDIMENTARY, AND STRATIFIED SYSTEMS.

		Quaternary		Superficial Deposits or Drifts: Recent and Pleistocene.		
		Kainozoic or Tertiary	{	Pliocene.		
				Miocene.		
				Oligocene.		
				Eocene.		
		Mesozoic or Secondary	{	Cretaceous.		
				Jurassic	{ Oolites.	
					{ Lias.	
				Permo-Triassic or New Red Sandstone Series.		
Primary	{	Palæozoic	{	Carboniferous.		
				Devonian.		
				Silurian.		
				Ordovician (or Lower Silurian).		
			Archæan		Cambrian.	
				Pre-Cambrian.		

Particulars of the many formations in Britain are given in a separate chapter.

The aqueous or stratified formations were accumulated under particular physical conditions, whether marine, estuarine, fresh-water, or terrestrial; and although they occur in definite sequence, some are locally absent through non-deposition and overlap, or erosion prior to the deposition of the overlying strata.

Fig. 1 shows the nature of overlapping beds, A being overlapped by B, B by C, and C by D. These strata rest irregularly on a mass of granite, G, from the shattered and fissured portions of which a spring issues where the cross is marked.

Geological formations are composed of layers of hard or soft rock, sometimes in alternating beds, with the harder layers cracked or jointed, and the softer layers thinly bedded or laminated, as in shale. They are disposed sometimes in great level tracts with horizontal stratification, and with an outcrop on the borders of a valley. Elsewhere they have been subjected to dis-

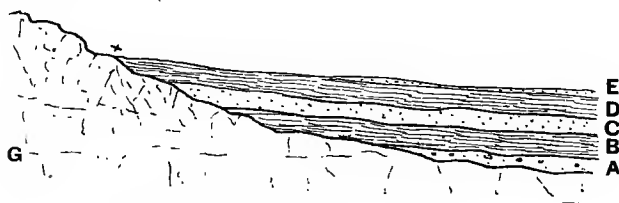


FIG. 1.—OVERLAP OF STRATA.

turbance, having a dip or inclination in a certain direction, and at an angle that varies between 1° and a vertical position.

They are sometimes bent into folds or arches, known as 'anticlines,' and into basin-like structures, known as 'synclines'—many varieties of which occur, according to the nature of the disturbances, the folds being sometimes so inclined that the strata are inverted, and the sequence is repeated.

Formations are likewise affected by faults or planes of fracture and displacement, usually with a hade or inclination from the vertical, but the dislocations some-

times approach the horizontal and give rise to overthrust, whereby an older formation is thrust over a newer. This structure becomes developed from inverted folds that are faulted.

Both joints and fault-planes may be enlarged into fissures by earth-movements, and often by the dissolution of calcareous rocks. As a rule these crevices decrease in depth.

Variation in the thickness of a formation or band of rock, as shown in the accompanying diagram (Fig. 2), may be due to original irregularity of deposition, as at B and C ; to ancient erosion (concealed), as at A, E, and F ; or to more recent denudation on the outcrop, as at D.

Where older rocks more or less eroded, and also inclined and perhaps folded, are covered by newer strata, the discordant position is known as an 'unconformity.' In the above section there are unconformities between A and B and at E.

The irregular surface at F is due to dissolution of a bed of limestone that is unconformably overlain by gravel.

Variation in character is sometimes due to the local induration of masses of sand, forming irregular beds, and sometimes huge spheroidal concretions or doggers of sandstone. This consolidation may be caused by calcareous siliceous or ferruginous matter, which fills up the interstices or pores of the strata. Thus, a loose water-bearing gravel may be locally hardened into a conglomerate or pudding-stone that holds water only in crevices.

Variation of strata is also due to the gradual passage horizontally and vertically of clays into marls or into

alternating clays and limestones; of sands into loams and clays; or of sands into calcareous sandstone and

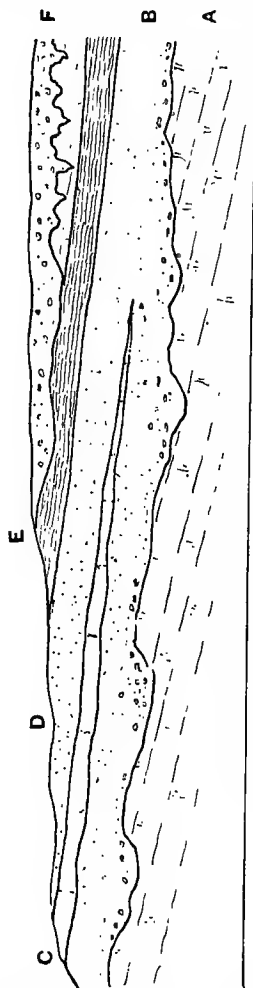


FIG. 2.—IRREGULARITIES IN THE THICKNESS OF STRATA.

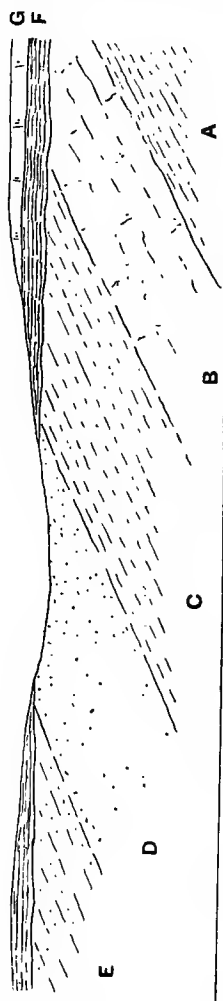


FIG. 3.—UNCONFORMITY AND OVERSTEP OF STRATA.

sandy limestone. It is also caused in sandy and in

oolitic strata by current or oblique bedding, when the deposits, laid down in shallow water, have been shifted irregularly by currents.

Unconformity is again exhibited when an inclined series of strata is abruptly truncated and covered by approximately horizontal formations, as in Fig. 3; there the newer beds, F and G, transgress or overstep the outcrops of the underlying strata, A, B, C, and E. A and C being shales, water is prevented from entering B; but it can gain access readily to D, and thence to E, these strata being sands and sandstones.

In some cases, owing to erosion, a harder formation may protrude to the surface through newer bordering

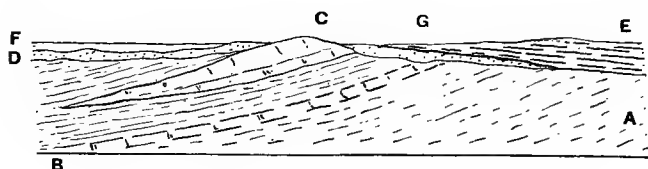


FIG. 4.—UNCONFORMITY OF STRATA AND INLIER.

strata that rest unconformably upon it, as in Fig. 4, where the limestone appears as an inlier. A well sunk between F and C would find water both in the sand D and in the limestone C; a well sunk at G would obtain a more limited amount of water from the sand and underlying rock-bed B; while a well at E would obtain no water from the strata shown, both A and E being clays.

In Fig. 16, p. 67, an inlier of Old Red Sandstone on the Mendip Hills appears at the summit of a denuded anticline, where the bordering strata are conformable.

The uncertainty of the underground structure, where great unconformity prevails, is shown in Fig. 5, where

the older group of formations was bent into anticlinal and synclinal structures and eroded prior to the de-

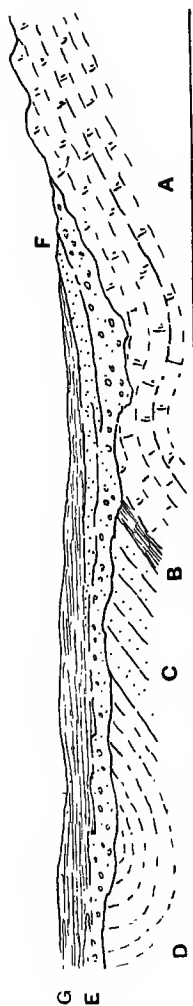


FIG. 5.—IRREGULAR STRATA OVERLYING ERODED SURFACE OF FOLDED STRATA.

position of the newer strata. A represents limestone, C hard sandstone or grit, E conglomerate, and F sandstone, and all might yield water, mostly from fissures; B, D, and G, represent shales, clays, and marls, that are impervious.

The Cotteswold Hills form a good example of the inclination of strata from an escarpment, where a series of formations may be seen to outcrop along the scarp, and to form a gentle dip-slope in the opposite direction. Fig. 21, p. 81, gives a diagrammatic representation of this structure. The erosion of the high ground at F has there led to the formation of an outlying mass or outlier, an example of which is also shown in Fig. 6.

In this illustration A represents the Upper Lias Clay; B, the Midford (or Cotteswold) Sands; C, the Inferior Oolite Limestone; D, the Fuller's Earth Clay; and E, the Great Oolite Limestone. An overflow spring from the Inferior Oolite and underlying Sands would be thrown out at the cross above the Lias Clay, and another spring

would be thrown out between E and D, at the base of the Great Oolite, the dip of the strata here directing the outflow.

The London Basin is a good example of a syncline, though the structure, a shallow trough, is much less

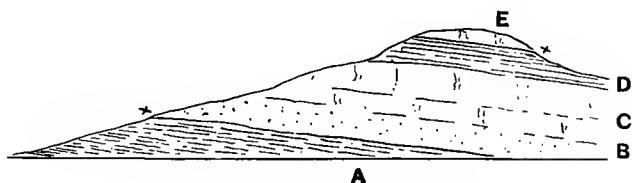


FIG. 6.—OUTLIER AND SPRINGS.

prominent when drawn to a true scale (see Fig. 34, p. 132).

The Isle of Wight displays in a more conspicuous manner the results of folding and disturbance which have brought the strata in places into a vertical position, as shown in Fig. 7.

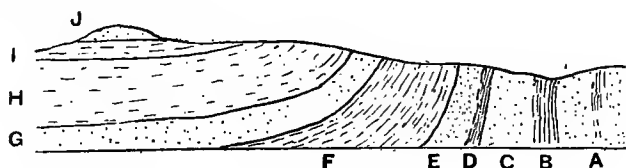


FIG. 7.—DISTURBED STRATA IN THE ISLE OF WIGHT.

A and C are Bagshot Sands, with included clay at B; D and E are Bracklesham clays and sands; F and G are Barton clay and sands; H and I represent Oligocene strata; and J, gravel and sand. The Oligocene strata yield small amounts of water here and there, but are mostly impervious; the overlying gravel and sand would yield limited supplies, the water being

mostly drained off in springs. Supplies would be stored in the sands G, E, C, and A, where the strata occur inland; on the coast the water would be drained off to sea-level, and, if pumped, salt-water would no doubt soon be drawn into a well carried below that level.

✓ The Dip, or inclination of the strata, is of importance in questions of water-supply, when a formation is composed of alternating layers of sand, sandstone and clay, or of clay and limestone; or where formations of different lithological characters occur in succession. In

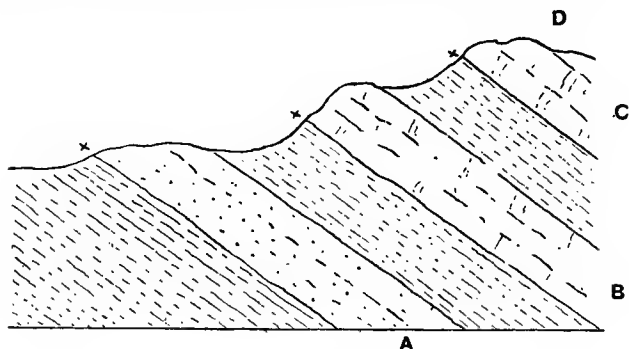


FIG. 8.—INCLINED STRATA AND SPRINGS.

Fig. 8 a series of strata is represented as dipping at about 35° . Springs would be thrown out from the sandstone A, and the limestones B and C, at the points marked by crosses; and a well or boring at D would obtain supplies of water from A, B, and C, which are separated by beds of shale.

The supply of rain-water taken up by a formation is influenced largely by the character and extent of the outcrop of the porous or pervious strata; the breadth, dependent on the thickness of the formation, varying

with the inclination and the shape of the ground. On a steep slope water will not so readily percolate into the ground as on a gentle slope. See Fig. 21, p. 81, where bed B (apart from its greater thickness) would more readily receive rain falling on its outcrop than bed D; and in Fig. 8 beds A and C would more readily take in rain than bed B. Springs from C would enter the upper outcrop of B, and those from B would enter A, if the lower strata were not already saturated. If the strata at C were subject to contamination, polluted water might thus be conveyed into strata at the lower levels.

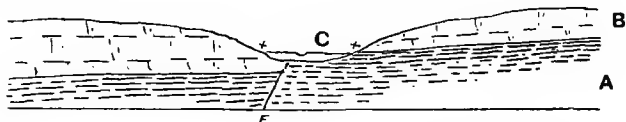


FIG. 9.—FAULTED STRATA AFFECTING AMOUNT OF UNDERGROUND WATER.

Dip may be of little or no importance where there is a great thickness of uniform porous strata undivided by impervious bands. (See Fig. 15, p. 58.)

Thus, geological structure, as will be readily understood, greatly affects the underground circulation of water. A fault, as shown in Fig. 9, has lowered the water-bearing strata on one side of a valley, and influenced the outflow of water on the other. In times of drought the limestone between B and C would be practically dry, while that on the opposite side of the valley would hold water up to the level of the Alluvium C. The outlets of springs after wet weather are marked by crosses.

Faults may bring clays against limestones or sand-

stones, and thus dam up supplies of water on one side, and arrest the percolation of water on the other. In some cases they divert the water to a lower horizon, and elsewhere near the sea-coast they may prevent the influx of sea-water. (See Figs. 38, p. 233, and 44, p. 301.)

Fissures, which are joints or faults widened by erosion, are of great importance in yielding free supplies of water in hard or dense rocks; occasionally, however, they may be filled with clayey material, and act as water-tight barriers. Attention should be given to the direction of joints as well as faults, as both influence the underground flow of water. Caverns in limestone have arisen from the dissolution of portions of the rock, sometimes along faults or joint-planes. (See Fig. 27, p. 94.)

In slaty rocks water has sometimes been encountered in fissures at considerable depths, fed from rain that has penetrated the shivered surface-beds or other overlying porous strata. It is, however, a very speculative proceeding to bore to any great depth in slate in hopes of encountering a water-bearing fissure.

✓ Geological formations are generally taken to include, not only the ordinary aqueous, sedimentary, or stratified deposits, but also the eruptive or Igneous rocks, and those known as Metamorphic.

The Igneous rocks for practical purposes are divided into the Granites and Greenstones, two great classes, with many subdivisions, intimately linked by intermediate varieties. As geological formations they receive similar designations all the world over, according to their mineral ingredients, and irrespective of age.

In the Granite group we may include granite, elvan,

syenite, felsite, and trachyte; and among the Greenstones, gabbro, diorite, dolerite, and basalt.

The great granite masses were intruded among sedimentary rocks at all periods; the older types have been altered into gneiss; the newer and ordinary types are represented by the granites of Cornwall and Devon, Aberdeen, Peterhead, and elsewhere; while still more recent masses appear in the granophyre of the Red Hills in Skye.

—Granites may hold supplies of water in fissures to a depth of about 500 feet, according to the physical

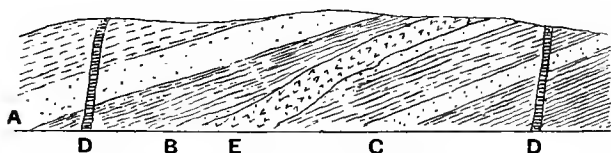


FIG. 10.—SILL AND DYKES OF IGNEOUS ROCK TRAVERSING SHALES AND SANDSTONES.

features of the country. They are much jointed, and sometimes present a structure resembling the bedding in stratified rocks. (See Fig. 1, p. 22.)

Other great intrusive masses belonging to the Greenstone group are met with, as in the gabbro of the Cuillin Hills in Skye. There also are great sheets of bedded basalt.

Both groups occur also in minor intrusions in the form of sills and dykes. Sills cut the sedimentary strata at various angles, and sometimes follow the bedding, as at E in Fig. 10, where a sill has traversed shales, cut through a bed of sandstone B, and then flowed evenly on its surface.

Dykes are usually found traversing the strata at high

angles or in vertical positions, as at D in Fig. 10. Sometimes, when harder than the bordering rocks, they stand out like walls; in other cases they may be eroded so as to form fissures.

Both sills and dykes may act as impervious barriers impeding the circulation of water at a depth below the influence of weathering agents. Thus, the dykes D would probably prevent the rain-water which percolates into the outcrops of the sandstones A and C from descending beyond their limits—that is, to the left of them, as shown in the diagram.

Dykes of igneous rock and veins of quartz-rock may thus be of use in damming up supplies of water in certain situations; and they may also prevent the inflow of water into adjacent porous strata. The sill represented in the diagram Fig. 10 would tend to keep out water from the lower part of the sandstone at B.

From a water-bearing point of view the igneous rocks are by no means unimportant; they hold much water in open joints and in the decayed superficial portions, whence springs are thrown out. In the greenstones the decomposition often gives rise to earthy material with included spheroidal masses of hard rock, and copious springs may be yielded. In some cases the volcanic rocks consist of loose ashly materials, more or less stratified, and these may be water-bearing.

✓ Metamorphic rocks are those which have undergone considerable changes by heat, or by pressure and heat, since their formation.

All rocks, indeed, have suffered change, but those only are termed 'metamorphic' that have been modified by contact with igneous rocks, or have been greatly changed by the additional effects of earth-movements

and heated waters, so that their mineral constitution has been chemically and mechanically rearranged. Metamorphic rocks thus include both igneous and aqueous formations, and are of all ages, the older rocks as a rule having undergone most change.

The Archæan rocks, for instance, comprise a complex of altered igneous and sedimentary rocks, including gneiss, schists, quartzites, and limestones (mostly altered into marble). The rocks possess a schistosity or foliation that is independent of any original planes of deposition, akin to the cleavage in slate, which is a product of pressure, and seldom coincides with the layers of sedimentation.

Supplies of water are obtained from crevices or decomposed portions of the schistose rocks.

In Wisconsin, where the crystalline rocks comprise granite, syenite, greenstone, mica-schist, etc., wells have been successfully made to depths of 20 to 50 feet and more. The whole or a large part of the water-supply is derived from the rainfall, which is held in the fractured surfaces or fissures of the rocks. The wells are usually dug, and sometimes made directly into the rocks through the decomposed surface portion, which forms a loamy or clayey soil; sometimes through the Glacial Drift, at the junction of which with the underlying crystalline rock, abundant supplies are commonly met with.¹

During the construction of the St. Gothard tunnel it was found that gneiss was decomposed in places to a depth of more than 1,000 feet from the surface, while in the Simplon tunnel, below 7,000 feet, much hot water was encountered.

¹ Dr. Samuel Weidman, *Wisconsin Geol. and Nat. Hist. Survey*, Bulletin XI., Econ. Series 7, 1903.

The limits of this volume would be far exceeded were any attempt made to deal generally with the water-bearing formations in different parts of the world. Lithological characters taken in conjunction with geological structure are all-important, but the illustrations taken from the British Isles, and mainly from England, exhibit the principal types of water-bearing formation and structure.

The older geological formations are as a rule harder and more compact, and more highly inclined and folded, than the newer formations; and the ground is more suitable for reservoirs than wells and borings.

The Secondary and Tertiary formations are the chief water-bearing strata in this country.

The Superficial Deposits, or 'Drift,' as elsewhere noted (see pp. 149, 227), are less regularly distributed than the earlier stratified or 'Solid' formations, among which the rock directly underlying Drift is sometimes referred to as the Bed-rock. The Glacial Drift is especially irregular. The superficial sands and gravels, and sometimes the talus or scree-material on hill-slopes, have yielded abundant supplies of water; but in many cases shallow wells in sands and gravels have been abandoned on account of contamination.

The Alluvial Deposits comprise alternations of sand, gravel, clay, silt, and peat, and under certain conditions they may yield good supplies, sometimes under artesian pressure along coastal plains. Shallow dug-wells in Alluvium are not to be commended, as the ordinary deposits grouped under this name form the flat meadow and marsh lands bordering a river, and these tracts are liable to be flooded.

The Soils, which form a thin covering to the geo-

logical formations, though of little or no importance from a watering-bearing point of view, are of consequence as regards their porosity and power of absorbing and transmitting water. They are due primarily to the decomposition of the underlying rocks, the weathered portions of which, known as the 'subsoil,' merge into the soils. The growth of plants and decay of vegetable matter, the influence of burrowing animals, and still more the action of micro-organisms, together with much wind-drifted material, have tended to give distinct characters to the soil as apart from the subsoil or strata beneath. Agricultural operations, with the application of various kinds of manure, have again greatly altered the natural or virgin soils.

The lands occupied by Quaternary, Tertiary, and Secondary formations are mostly under cultivation; the sands and gravels, the loams and limestones, being largely arable grounds, with some meadow, pasture, woodland, heath, and common. The areas of clay are most largely under grass, with some extensive tracts of woodland, arable lands, and commons. The high Chalk Downs are chiefly pasture-lands.

The older rocks, which form ground that may be cultivated in the lowlands, rise up more often into high moorlands and mountains. They include in Britain the Coal-fields and a good deal of the metalliferous mining areas.

CHAPTER IV

THE DISPERSAL OF RAIN ON THE SURFACE AND UNDERGROUND

IN the previous chapter the general structure of the earth's surface has been described, and it has been pointed out that the irregular features of the land are formed by rocks of varying texture, permeability, extent, and inclination. These different rocks which form the solid ground receive the rainfall that percolates through the soil, or descends directly on the bare surfaces of rock. Under natural conditions the porous and jointed strata in process of time have become charged with water so far as possible, according to their disposition; but impervious coverings and faults, and the form of the outcrop in many instances, prevent the saturation of the entire mass of a formation. The surplus water that falls on saturated strata overflows in the form of springs.

Where the soil rests on an impervious foundation, such as clay, marl, and certain loams, a good deal of rain will be absorbed after dry weather; otherwise, if the strata be moist, the rain will run off the surface into the streams where the ground is sloping, or collect in pools where it is flat.

After heavy and long-continued rain, the soil and ground beneath, whether formed of porous or im-

pervious strata, may be so saturated that the rain is rapidly carried away in rills on the surface to the brooks and streams; and this occurs on some of the sandy districts of the Wealden area, on the Bagshot Beds near Woking, and on the pebbly gravels of the Addington Hills and Croham Hurst near Croydon. On steep slopes and in the downpour of a 'cloud-burst' the rain may fall so rapidly that percolation cannot take place. Rain falling on frozen and snow-covered ground also flows quickly away. In such cases floods often result.

While the rainfall thus supplies the streams and rivers, and is the main source of underground waters, the proportion that may be available above or below ground for practical purposes varies greatly in different regions. This amount depends on the evaporation, and on the absorption of moisture from the soil and subsoil by vegetation.

In questions of water-supply we have therefore to consider—

1. Evaporation and absorption by vegetation.
2. Direct run-off by surface streams.
3. Percolation, infiltration, and absorption by strata.
4. Outflow from springs and seepage, and the general direction of underground flow.

The total 'run-off' available for water-supply from streams, lakes, and rivers, will be included under headings 2 and 4.

The amount available for underground supplies would practically be that registered as 'percolation,' being the quantity which would naturally escape in springs and seepage from the saturated strata, the level or plane of saturation being dependent on the geological

structure. The amount drawn out by other wells or borings has also to be considered. Moreover, a small and negligible quantity of water which enters the rocks may pass into chemical combination with anhydrous minerals.

It is evident, when we bear in mind the local and seasonal fluctuations in rainfall, the differences of climate, of geological structure and physical features, that estimates of the available quantity of surface or underground water cannot be precise. It is comparatively easy to calculate the amount that under ordinary circumstances is not likely to be exceeded, but it is more important to estimate the minimum amount that is available.

In the United States, Mr. G. W. Rafter (1903) has considered the subject under the headings of (1) *Storage period*, December to May, when there is much rain, the evaporation and absorption by plants are relatively slight, and there is a large run-off, especially in times of flood; (2) *Growing period*, June to August, when there is little rain, the evaporation and absorption by plants are most marked, and the ground-water is low; and (3) *Replenishing period*, September to November, when there is a fair amount of rain, the ground-water rises, and the run-off increases. The actual results, of course, vary from year to year, but the general principles may be borne in mind, in their application to particular countries.

EVAPORATION AND ABSORPTION BY VEGETATION.

In the British Isles evaporation and absorption by vegetation are most potent as a rule in the summer; a less proportion of the rain percolates into the strata,

although the actual fall of rain in summer may be greater than that in winter. The autumn rains penetrate more deeply into the dry and often fissured surfaces of the ground, and on them, and more especially on the winter rains and snow from November to February, the underground supplies and the permanent springs are dependent. Much percolation may take place from melting snow on porous strata. On the other hand, on flat or gently sloping impervious ground, rain may at times be almost wholly evaporated or absorbed by vegetation.

Percolation is therefore dependent on the nature and state of the ground, and it is affected more largely by the character than by the actual amount of the rainfall. Steady and continuous rain will better feed the underground stores than heavy and torrential downpours.

The influence of wooded forests on rainfall is of considerable importance, and it is admitted that the excessive cutting of timber has made the ground much drier, and in tropical countries has rendered the climate warmer. By the destruction of trees both soil and subsoil are apt to be washed away, gullies are formed, and the rainfall in consequence drains more quickly off the land into streams and rivers. These are rendered more torrential in character in rainy periods, and their flow at other times is considerably diminished, brooks having in some cases ceased to run. Hence arise periods of flood and drought, results which in hilly and mountainous regions, and in those subject to periodic heavy rains, are more pronounced. Woodlands, according to Rafter (1903), show a larger run-off than deforested tracts with the same rainfall.

The evidence to show that the cutting of woods even on a large scale has materially affected the amount of rainfall is somewhat conflicting, although from 2 to about 12 per cent. of extra rain has been estimated to occur over some large areas of wooded ground as compared with the rain on adjacent open ground. Much, however, depends on the locality, the elevation, and the temperature.¹

It is clear that plants obtain most of the water they contain from the soil, and, according to R. Warington, 'timber felled in the driest time seldom contains less than 40 per cent. of water.'² Yet plants also after very dry weather absorb rain-water through their leaves. Under ordinary conditions a large amount of water is transpired or evaporated from plants, whereby the atmosphere is somewhat cooled, and mists or clouds are then apt to discharge more water over the woodlands than over the open lands.

Thus the process is complicated. While plants draw moisture from the soil, and thus tend to decrease the amount of ground-water, they tend to retard by their leaves the rapid downfall of rain, and also afford shelter from sun and wind, to check the subsequent evaporation from the soil. In this way they have a tendency to conserve the water, to promote humidity, and to equalize the flow of water into streams.

Capillary action, whereby moisture in some cases descends from the soil, in other instances rises from the saturated substrata, should here be mentioned.

¹ See *Nature*, December 30, 1897, and February 1, 1906; Report of Committee on British Forestry, 1902; and Report by H. B. Muff [Maufe], 1908.

² 'Chemistry of the Farm,' fourth revision, 1907, pp. 1, 9, etc.

As quarry-water or water of imbibition, this moisture is well known in certain building-stones, and in porous bricks of dwelling-houses that are not provided with an effective damp-course. The moisture coats the minute pores of soils and rocks, or the particles of which they are composed.

Referring to dry summers in the south of England, Mr. A. D. Hall (1903) has remarked that in the Thames Valley gravel, with the subsoil water 16 or 20 feet below, there was no appreciable uprise of moisture to the surface; whereas in the Chalk, where the plane of saturation was 200 feet below the surface, there was a steady capillary rise of water through that fine-grained rock.

Clays and loams absorb and retain moisture for 2 or 3 feet above the saturated masses, and sand from 18 inches to 2 feet. The coarser materials retain less; but Warrington (1907) remarked that the quantity diminishes when the particles exceed a certain amount of fineness, and that capillary action is most effective in silty soils, which consist of very fine uniform particles without clay. In peat the capillarity is great; and in humus, the black or brown organic matter formed chiefly by the decay of vegetation in the soil, much aqueous vapour is absorbed. Sandy and gravelly soils derive little or no moisture from the air.

As further pointed out by Mr. Hall, 'The subsoil acts as a regulator to the amount of water contained in the surface layer, absorbing the water which descends by percolation during rainy periods, and giving it up again by capillarity to the surface soil during periods of drought.' Moreover, 'When the ground has become dried to any depth in the summer, percolation may be much hindered by the air within the soil and the want

of a continuous film of wetted surfaces to lead the water down by surface tension.' Moisture may thus be retained in soils at some distance above the saturated substrata.

Agricultural operations through drainage, tillage, and manuring, tend to render pervious the more retentive clayey soils and to increase capillarity. In some cases drainage, by carrying off the surface water, may diminish evaporation, but it assists in rendering certain soils more porous.

The amount of evaporation, aided as it is by vegetation and capillarity, thus varies according to the composition and texture of the soil, and the nature of the subsoil, which if retentive will more often lead to a saturation of the soil. In such a case, as remarked by Warrington, evaporation from the land would exceed that from a surface of water.

EVAPORATION AND PERCOLATION.

Observations at the experimental station Rothamsted, Harpenden, on a mixed soil and subsoil of Clay-with-flints and Chalk, show with a rainfall of 30·29 inches :

	Inches.
Annual average percolation	13·61
Annual average evaporation from surface free from vegetation	16·68

According to the Reports of the Director, Mr. A. D. Hall, in 1907, with a rainfall of nearly 27 inches, the percolation through soil 5 feet deep was 11·39 inches; and in 1909, with a rainfall of 28½ inches, the percolation was 15·66 inches.

At Nash Mills, Hemel Hempstead, the general results are as follows :

	Inches.
Annual rainfall	28·18
Annual percolation	6·94
Annual evaporation and absorption by grass	21·24

These figures are subject to great seasonal variations, the amount of percolation at Nash Mills being sometimes as low as 3 inches per annum.

Sir John Evans was of opinion that, in the Chalk areas of the London Basin, it was safest to estimate for an available water-supply based on the dry-year proportion, of only 4 inches of annual rainfall.¹ This would certainly be on the safe side, as 7 or 8 inches might usually be relied upon. The average amount of percolation in the Chalk of Hertfordshire is estimated at 9·5 inches out of a rainfall of 26·4 inches.

Experiments on percolation through cubic yards of Chalk and gravel, grass-covered, have been carried on for thirty years at Croydon by Mr. Baldwin Latham (1909), who has recorded that, with an average yearly rainfall of 25½ inches, the average annual amount of percolation through the Chalk gauge was 10·84 inches (42·6 per cent.), and through the gravel 10·34 inches (40·6 per cent.). He found that the rate of percolation was governed by the rate of rainfall, and that as a rule the largest percolation took place during October to March.

Evaporation from a surface of water during the same period was found to be 18·14 inches, and the condensation 0·36 inch: the greatest amount of condensation

¹ Address, *Quart. Journ. Geol. Soc.*, xxxii., 1876; see also lecture on Physiography, *Proc. Inst. Civ. Eng.*, January, 1885.

being 1·295, and the least 0·095. The increase to water-surfaces by condensation of moisture is sometimes termed 'Negative Evaporation.'

According to L. F. Vernon-Harcourt (1896), evaporation is greater from a surface of water than from the ground in summer, and greater from the ground than the water in winter. At a depth of 2 or 3 feet water does not appear to be subject to evaporation.

Much, however, depends on the country and the rainfall, as with a dry winter there may be more evaporation than during a summer season of rain. The effects of wind and temperature are naturally of great importance.

Evaporation appears to be greater in shallow and in running water than in still deep water. In reservoirs and lakes it may amount to $\frac{1}{10}$ inch or more per day, but not more than 20 inches per annum in Britain. In India, as noted by Sir A. R. Binnie (1887), it may amount to 60 inches per annum, and in the central desert regions of Australia it has been reckoned to be as much as 100 inches (see p. 257). In Egypt the mean evaporation from expanses of water was estimated by Mr. B. F. E. Keeling at about $\frac{1}{6}$ inch daily.¹

In questions of water-supply the nature of the subsoil is all-important. In some of the Oolitic uplands where the fissured limestones are barely covered with a brash, water readily penetrates in the joints or 'lissens,' as on the Cotteswold Hills near Minchinhampton. Again, on the surface of the Carboniferous Limestone of West Yorkshire and the Lake District, bare and fissured rocks occur over large areas, and the bulk of the rain readily descends into the strata (see p. 219).

¹ *Nature*, September 30, 1909, p. 403.

During times of drought a surface formation of clay, 3 feet or more in thickness, may become so fissured that rain for a time may be conveyed downwards into underlying porous strata, a fact shown sometimes by the open and weathered joints of underlying limestones that are shaped like miniature caverns. In some cases clay is carried downwards into the rocky fissures, and then tends to arrest the flow of water from the outcrop of the porous strata. Examples of these features may be seen in the Great Oolite Limestone and overlying Great Oolite Clay in the neighbourhood of Bedford.

POROSITY OF ROCKS.

Apart from open joints or fissures and faults, the amount of rain that percolates into the ground depends on the texture of the soil and underlying geological formation. Soils are notoriously variable with regard to depth and constituents, and although the substrata are often of a mixed nature, there are formations of fairly uniform character which extend over wide areas. These differ greatly in water-bearing capacity, which depends, not on the quantity of water they can absorb, but on their porosity. All rocks, even granites, appear to have a certain amount of porosity, holding water mechanically in tiny crevices, and, as a rule, the finer and the more uniform the grain of the rock, the greater the amount of water that can be imbibed.

Ordinary clay, such as that composing our great argillaceous formations, the Keuper Marl (often but little calcareous), the Lias, Oxford, Kimeridge and London Clays, may absorb almost as much water as any rock. Clays are porous, but not pervious.

The London Clay when saturated holds from 6 to 10 inches of rainfall in a cubic foot, and when drained a little less than 2 to $2\frac{1}{2}$ inches.¹ Hence its expansion and shrinkage at the surface. China clay is said to hold as much as 70 per cent. of water. The water so absorbed is, however, of no practical use in the matter of a supply, and no one would think of digging a well in clay for such a purpose.

The amount of water that can be held depends on the shape and extent of the pore-spaces, or, in other words, on the shape of the grains, rock-fragments, or stones, of which the rock or soil is composed. The mean diameter of these component materials is known as their 'Effective Size.'

In clays and loams, in certain very fine sands and silt, also in Chalk, the pores or air-spaces are fine, and the amount of water that can be held is large; yet, owing to the greater resistance to the passage of water and air, clay is practically impervious, while some sands, especially those of the nature of silica-clay, which is a powder of fine quartz, and Chalk, may become like putty or whiting, and part but slowly with water.

Many particulars have been published with regard to the amount of water that can be retained by various rocks, and those which, yielding it more or less freely, are termed 'water-bearing' may hold from 10 to 50 per cent. or more of water in bulk. So long as the particles are not too fine, as in some cases previously mentioned, the larger amounts of free water are held by rocks

¹ A. D. Hall and F. J. Plymen, 'Soils of Kent' (S.E. Agricultural College, Wye), 1902.

of fairly uniform grain, irrespective of bulk, as the pore-space is then of greatest capacity.

Thus, coarse sand or pebble-gravel would hold more water than a mixture of the two, and than gravel composed of subangular materials of irregular shape. A great deal depends on whether the strata are loosely aggregated or compacted under pressure, as in the former case their porosity is much greater; and they transmit water more freely.

Geological formations, however, are notoriously inconstant in character, and the experiments that have been made afford only a general indication of their water-bearing capacities. Variable indeed are the sizes of grains of sand and stones in gravels, and also of grains in oolite, although there is considerable uniformity over large areas in the case of some of these formations, as in Blown Sands, in certain Eocene and Wealden Sands, in the Midford Sands, the Great Oolite of Bath, and some pebble-beds.

Under particular conditions two-thirds, or even more, of a rainfall may sink into sand; but it may be said that there is every gradation from gravel to coarse and fine sand, and the capacity for yielding water is subject to considerable variation. Hence we find in records of well-borings that there are quicksands and dead sands, the former 'running' with the amount of water they hold, the latter approximately dry.

The porosity as noted by Slichter (1902) is thus reckoned: If a gallon of sand when saturated will hold $\frac{3}{10}$ of a gallon of water, the porosity is 30 per cent. If a cubic foot of sandstone will hold $\frac{1}{4}$ cubic foot of water, the porosity is 25 per cent.

The following table, drawn up by Professor F. H. King, has been quoted by Mr. G. W. Rafter (1903):

	Depth, Inches.	Per Cent. of Water.	Inches of Water.
Marly loam	12	41·3	5·88
Reddish clay	12 to 24	28·1	5·03
Do.	24 to 36	28·4	5·07
Clay with sand	36 to 48	24·8	4·67
Very fine sand	48 to 60	17·4	3·76
			24·41

It gives the water-capacity of undisturbed superficial strata lying below the plane of saturation, thus showing the amount of water which may be contained in such deposits under natural conditions when they are fully saturated.

In the table on p. 49 are given the results of some experiments on the amount of water that can be held in certain rocks under artificial conditions.

RATE OF PERCOLATION.

According to experiments made by Prestwich (1886), coarse sand of the Lower Greensand held 2 to 3 gallons of water per cubic foot, and transmitted at the rate of from 8 to 14 inches per hour; slightly argillaceous Upper Greensand held 3 gallons per cubic foot, and percolated at the rate of $3\frac{1}{2}$ inches per hour; and fine and slightly argillaceous Thanet Sand held $2\frac{4}{5}$ gallons per cubic foot, and the percolation was at the rate of $1\frac{1}{2}$ inches per hour.

	Per Cent. by Weight.	Per Cent. by Bulk.	Gallons per Cubic Foot.
Gravel (without sand)	—	25 to 45	2.09
Gravel and sand ...	—	25	—
Sand, fine ...	—	—	1.8 to 2.10
Sand, coarse ...	—	25 to 45	2.10 to 3.0
Sandstone ...	—	30 to 60	0.50 to 1.37
Keuper ...	—	—	0.81
Bunter ...	—	—	0.73 to 0.77
Old Red Sandstone	—	11½	—
Limestone, compact ...	—	—	0.12 to 0.54
Chalk ...	20	50	2.0 to 2.5
Magnesian Limestone ...	—	18 to 25	1.13 to 2.5
Oolite ...	—	—	1.11 to 2.1
Bath Stone ...	—	31	1.0 to 2.1
Portland Stone	—	—	1.13 to 1.28
Loam ...	—	40 to 60	—
Clay ...	19.5 to 24.5	60	1.87
Shale ...	6 to 8	—	—
Slate ...	—	—	0.01 to 0.05
Granite, hard ...	0.37	1 to 3½	0.04 to 0.08

Mr. S. C. Bailey has estimated that it would take 15½ hours for water to pass through a bed of unfissured chalk 1 foot thick.¹

These instances indicate the slowness of percolation without pressure.

Chalk under hydrostatic pressure of 40 pounds to a square inch, according to Mr. Baldwin-Wiseman (1907), would store nearly 3 gallons of water per cubic foot, or about 1 gallon more than under ordinary conditions.

Naturally, water circulates most freely through coarse-

¹ *Engineer*, April 6, 1906, p. 336.

grained rocks, where less friction is encountered than in the finer materials; but the flow is retarded by the pressure of air, and also by the amount of saline constituents in the water. (See p. 164.)

It is reckoned that water can as a rule be more freely drawn from sandstone than from limestone, in the absence of fissures.

The rate of percolation or movement of water through unfissured strata is in general very slow, but it is more rapid when the temperature is high, and more rapid in proportion to the head of water, the inclination of the strata, and the means of escape. According to Slichter (1902), the rate of underground flow of water at a temperature of 70° F. is about double that at 32°.

Increase of flow has been shown to take place only within certain limits, until the 'critical pressure' is reached, and this differs according to the nature and thickness of the strata.

The flow in gravel with a gradient of 100 feet to a mile has been reckoned by Slichter to vary from $2\frac{1}{2}$ to $63\frac{1}{2}$ miles per year. The underground flow below the Arkansas River, with a gradient of 7 feet to a mile, was estimated to be from about $\frac{1}{5}$ to about $\frac{3}{4}$ mile per year. In another instance the velocity below the deep channel of the Mohave River was estimated at from under $\frac{1}{2}$ mile to rather over 4 miles per year.

The underflow, as remarked by Slichter, may be large in the mountainous parts of a stream where the gravel is coarse, but on the whole the velocity is small and the amount commonly exaggerated.

In fine sand, with a slope of 10 feet to a mile, the velocity of ground-water has been reckoned at 52 feet

in a year, in coarse sand at 845 feet, and in fine gravel at rather more than a mile a year.

Prestwich (1872) remarked that the well at Grenelle in Paris, 1,798 feet deep, derived its supplies from the rain-water falling on the Lower Greensand of Champagne, and travelling about 100 miles underground before reaching Paris.

Through fissured rocks the rate of percolation or flow will be dependent on the head of water and the size of the fissures. On a broken rugged foreshore of granite rocks, where pools of sea-water are left at different elevations at low-tide, the slow drainage through chinks and cracks may be observed.

In decomposed igneous rocks the seepage is slow, and the ground-water is well maintained. This is to be observed in Jersey.

The effects of drought thus variously affect different formations.

Owing to the many variations in the texture of the rocks, in the geological structure, the rainfall, and in the amount of hydrostatic pressure, the theoretic results of experiments on the rate of percolation and flow are not of precise practical value and application. No uniform rate of flow can be depended upon.

The available underground water is that represented by percolation, which would be independent of the water of imbibition, and in the ordinary course of nature would rise above the permanent plane of saturation, and be given out in the form of springs.

The surface run-off may amount to $\frac{1}{6}$ or $\frac{1}{7}$ of the rainfall, when the ground is formed of a series of pervious and impervious strata, and much more where the

catchment area is formed mainly of dense and impervious rocks.

The annual discharge or total run-off, which in Britain is estimated at from $\frac{1}{4}$ to $\frac{1}{3}$ of the rainfall, includes the surface flow and the underground outflow (seepage and springs); but of course the underground flow must vary according to the amount of water pumped.

Under natural circumstances the amount of evaporation and absorption by vegetation may be rather more than half the rainfall. It is estimated to vary in Britain from 10 to 18 inches, and may be reckoned generally at 14 inches. The amount that may percolate is estimated at $\frac{1}{4}$ or $\frac{1}{5}$ of the rainfall. Therefore we may roughly reckon the rainfall to be dispersed as follows:

Evaporation and absorption by vegetation	=	$\frac{8}{14}$
Surface run-off	... ..	$\frac{2\frac{1}{2}}{14}$
Percolation	... ..	$\frac{3\frac{1}{2}}{14}$

Again, if the mean average rainfall be 30 inches, and we deduct $\frac{1}{5}$ for reduction in quantity during three consecutive dry years (see p. 11), we have 24 inches to deal with. Allowing $3\frac{1}{2}$ inches for run-off and 14 for evaporation and absorption by vegetation, there remain a little over 6 inches for percolation and underground supply.

PLANE OF SATURATION, OR WATER-TABLE.

All the water that passes through the soil into porous and permeable strata below is known as Ground-water. This water is upheld at different levels according to the

geological structure; it may be a foot or two beneath the surface, when it is simply subsoil water, or it may be several hundred feet. The ordinary level at which water will stand in the saturated permeable rocks below the surface depends upon the position of the first impervious layer. In Fig. 11 water will be held in the gravel B at a level dependent on the outlets afforded for springs in bordering valleys, and shallow wells will derive most water from the deeper portions of the gravel where it rests in hollows of the clay A.

Where the land is formed of an alternating series of porous and impervious strata, with outcrops on the slopes of a valley, there will be different levels of



FIG. 11.—SHALLOW-WELL WATER.

underground water, regulated by the upper exposed portion of each impervious layer. (See Fig. 21.) Where it is formed of a fairly uniform thick mass of porous strata, as in the case of the Chalk Downs, the ground water-level of the higher uplands may be at a considerable distance beneath the surface. (See Fig. 13.)

The ground-water therefore may occur at various heights in hilly ground, or it may correspond practically with the level of the streams and rivers that intersect the land. The more or less weathered belt subject to the influence of atmospheric agents and ground-water is sometimes termed the 'zone of hydration.'

According to their geological position, whether hori-

zontal or inclined, the porous strata which outcrop at the surface are all liable to be more or less saturated with water, and the overflow from these strata issues on the hillsides or along the low margins of valleys in the form of springs, to which attention will be specially drawn.

Where, from the level disposition of the porous strata, they are liable only to partial saturation, we may have a sequence from the surface as follows :

Soil.

Unsaturated porous strata (subject to capillary action).

Saturated porous strata.

Impervious strata.

This may be regarded as the ordinary condition in horizontal or gently inclined strata, although in certain positions, after long-continued rain, porous beds may become saturated above the level at which springs would ordinarily issue.

In low-lying situations, Chalk, gravel, or other porous formations, may be permanently water-logged.

The level at which water stands in porous or much-jointed strata, whether in high or low ground, is known as the *Plane of Saturation* or *Water-Table*.

Being dependent on the rainfall, this water-plane naturally fluctuates more or less, according to the texture of the strata and the facility with which the surplus water can escape in the form of springs, and in the undefined oozing known as 'seepage.'

The water-table is far from level unless in very dry seasons, but has an undulating surface corresponding, to a certain extent, with the irregularities of the ground

where formed by porous strata, although in less pronounced form. (See Fig. 12.) It is influenced also by undulations on the floor of impervious strata.

Fig. 12 is intended to show in diagrammatic form the water-table in the Chalk of the North Downs. The strata represented are: A, Gault; B, Upper Greensand; C, Chalk Marl; D, main mass of pervious Chalk; E, Lower London Tertiary strata (Thanet Sands, Woolwich and Reading Beds, and Blackheath Beds); F, London Clay. Springs are given out at the points marked by crosses, from the Upper Greensand, from the Chalk at a higher level, and from the uppermost beds of Chalk and Thanet Sands, etc. The plane of saturation or water-table in the Chalk, marked GG, is thus independent of the dip of the strata, and is regulated by the outcrop of the Chalk Marl below, and the outcrop of the London Clay, or of clays in the Woolwich and Reading Series, above.

The contours and gradients of the water-table are subject to modification by the rainfall,

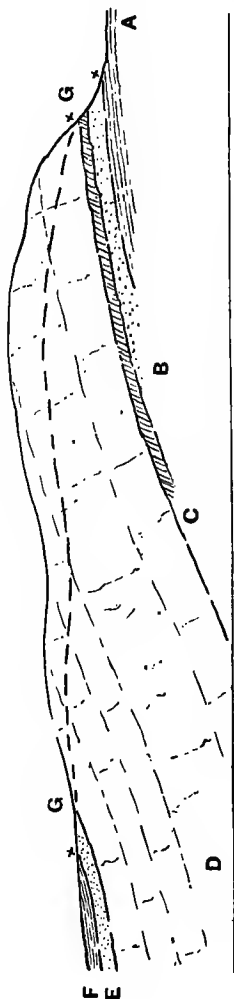


FIG. 12.—PLANE OF SATURATION IN CHALK DOWNS.

whether local or general, and to some extent by the porosity of the strata. Thus, the head of water which influences the underground flow will vary in different places according to the precipitation of rain, while in times of drought the level will sink until the springs become weak or cease to flow.

The permanent water-table or dry-season level acts to a certain extent like an impervious stratum, and the additions of water made to it will move in one direction or another along the hydraulic gradients according to the local water contours. This movement or subsurface zone of flow is independent of the general underground flow that may be due to the inclination of the strata, and to distant natural leakage at a lower level, and independent of that due to the pumping of water from wells.

The underflow may naturally be in one direction to the outlets formed by the lip of inclined impervious strata below, as in Fig. 19. Where outlets exist in two or more directions, the underflow will be modified accordingly, as in the case of horizontal strata in outliers, in a sequence of strata where the structure is that shown in Figs. 6, p. 27, and 21, p. 81, in basins, whether the structure be that simply of an impervious foundation filled with porous strata, or that of an artesian syncline where the porous strata are to a certain extent covered by clays, as in Fig. 34, p. 132.

Underground water, due in the first instance to percolation and gravitation of rain from higher to lower levels, is therefore subject to considerable diffluent movements, except in those portions that are pent up at a distance below ground where there is no second natural exit. The movements are influenced by the

geological structure, and largely by the floor of impervious strata, whether flat, undulating, or sloping. They are caused by the outflow of springs, and artificially by the abstraction of well-water. Locally, movements may be caused by artesian inflows along planes of dislocation, or the uprising of thermal waters from similar fissures. Minor effects are caused by capillary action.

The direction of underground flows, whether natural or caused by pumping, is of great importance in connection with well-sinking and boring, and possible sources of contamination.

The gradient of the water-table in a Chalk country along the dip-slope may amount to 10 or 20 feet per

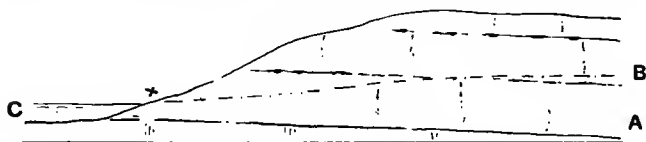


FIG. 13.—LOW-LEVEL PLANE OF SATURATION.

mile, as mentioned by Mr. H. J. Osborne White in the country near Basingstoke. From the higher grounds towards the scarp, in the direction opposite to the dip-slope, the gradient may be much steeper. (See Fig. 12.)

Where the main features are formed wholly of porous strata, whether sands, sandstones, gravel, or limestone, with no clay-partings or hard bands to arrest the downward percolation, the streams and rivers, which have cut ravines and valleys, mark the approximate plane of saturation, although it has a gradient towards the lower ground when the bottom-water appears at the surface, as at C in Fig. 13.

Here A represents a limestone-formation, B the plane

of saturation, and the cross marks the outlet of a spring.

Near Reading, for instance, the level of underground water in the Chalk is approximately that of the Thames.

On this account we find streams and rivers flowing over tracts of limestone, as in the dales of Derbyshire,

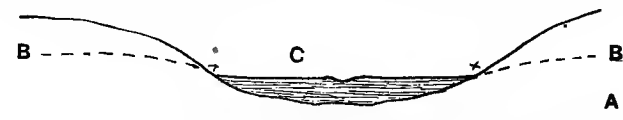


FIG. 14.—PLANE OF SATURATION AFFECTED BY ALLUVIUM IN VALLEY.

over the Chalk at Dorchester, on Salisbury Plain, in the Valley of the Thames and its tributaries, at Lewes and other places, where the streams traverse these water-logged porous formations.

In many cases streams carry sufficient mud or silt from higher parts of their courses to clay their beds

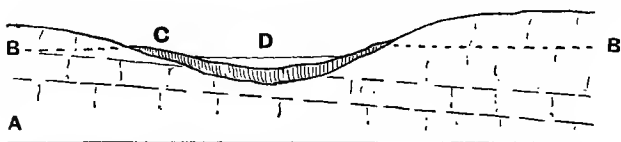


FIG. 15.—PLANE OF SATURATION AFFECTED BY DRIFT IN VALLEY.

over porous strata. Where a valley excavated in porous strata contains a thick bed of such alluvial mud, the water-level on the borders may be slightly higher than that of the stream itself, as shown in Fig. 14. The A represents Chalk; B, the plane of saturation; C, the alluvium; and the crosses mark the springs.

Clayey or marly material, as at C in Fig. 15, may

also be washed down the slopes of an otherwise dry valley, and locally raise the ground-water in adjacent land. In this illustration A is limestone; B, the dry-season plane of saturation; and D, an alluvial flat with stream.

Where embanked, the river may be higher than the level of adjacent springs, under somewhat similar geological conditions.

In a boring which was carried about 300 feet into the Chalk, on the borders of the Misbourn Valley, by Great Missenden Abbey, as I am informed by Mr. George Barrow, water rose 2 feet above the surface of the ground, whereas at a level about 5 feet lower, water sinks into the ground. This is probably due to the fact that the bottom of the valley is occupied by gravel which may be lined above the Chalk with loam or clay.

CHAPTER V

RIVERS AND UNDERGROUND CHANNELS, SWALLOW-HOLES, PIPES, BOURNES, AND DUMB-WELLS

THE question of the line of watershed or water-parting is often difficult to decide, as it may indeed vary from time to time in certain districts, according to the local rainfall on an upland tract of porous strata, and may not correspond with the highest range of elevations. (See Fig. 21.) Thus, the rainfall on one drainage area may be diverted by springs into another area.

On an impervious tract the surface-divide would be defined by the physical features.

Etchilhampton Hill, near Devizes, is formed of Lower Chalk, whence issue springs that act as feeders, one to the Kennet and Thames, a second to the Wiltshire and Hampshire Avon, and a third to the Bristol Avon. It would not be possible to indicate at the surface the position of the water-partings.

Lake Buenos Aires, on the borders of Chile and the Argentine Republic, has been referred to by Sir Thomas Holdich as presenting remarkable features in regard to the water-parting. The lake draws most of its waters from glaciers farther north in the Andes, by means of the River Fenix, which after flowing about thirty miles 'divides into two channels, one flowing to the lake, and

through the lake to the Pacific, and the other to the Atlantic.' Thus, for some distance 'the river itself becomes the actual water-divide of the country.'¹

Of streams that course on either side of the High Street at Chard in Somerset, one flows into the River Parrett and the Bristol Channel, the other into the Axe and the English Channel.

The Little Ouse and the Waveney, the one draining into the Wash, the other into the North Sea at Yarmouth, appear to rise in a low tract of gravelly and marshy ground at Lopham Ford, to the west of Diss, along the course of a valley that separates Norfolk from Suffolk. The tract has been modified artificially by dykes and by the low embankment of a road, but the valley, as remarked by the Rev. O. Fisher, 'intersects the watershed at right angles.' The Little Ouse, however, takes its rise in three brooks on the south, that unite near Botesdale, and flow to the low tract from which the head-waters of the Waveney issue. It would seem to be a case where the Waveney has gradually worked back, so as to encroach on the watershed of the Little Ouse—a process that may have been facilitated by erosion during the Glacial period. Nevertheless, springs must often commence near together beneath pervious strata ; while on impervious strata the sources of rivers may be almost wholly above ground, except for the seepage from the soils.

✓ Rivers differ greatly in character in accordance with the physical features and nature of the strata in the drainage area. In mountainous and hilly districts, where the rocks, though fissured, are mostly hard, and the gradients of the stream channels steep, the rivers are

¹ *Geograph. Journ.*, 1905, p. 71.

rapidly swollen by rain, and less rapidly dwindle when the supply ceases, a certain amount being held in peaty ground, shivered rock, and fissures. The run-off is copious.

In the lower plateau grounds, where alternations of more porous with impervious strata occur, there are often to be found dry upland valleys with permanent springs, and streams at lower levels.

Rivers like the Thames, which are fed largely by springs, receive the water slowly, and maintain their flow. The flow of the Thames, as noted by Dr. W. J. S. Lockyer, lags five months after the rainfall.¹ In clay-vales, where the streams depend most largely on direct rainfall and surface run-off, they are liable to rapid diminution, and sometimes disappear in times of drought.

In some regions, as in Oregon, the streams in a dry summer may be maintained by the melting of snow in the mountain regions. This is also a periodic cause of floods, as in the case of the Indus, which receives waters from the Himalayan snows.

Rains and torrents from melting snow in mountainous areas may descend to sandy plains, where the whole of the flow disappears, in part from evaporation, mainly by percolation.

‘In an arid region’ (as noted by Slichter, 1902) ‘the surface stream may gradually disappear, until a dry wash through the valley, only occasionally swept with floods from the mountains, marks the general course pursued by the silent underflow.’ What are known as ‘Sheet-floods’ are produced on arid sandy plains, where there are no defined water-courses, after

¹ *Nature*, June 22, 1905, p. 178.

heavy rain on neighbouring mountains. Such floods, as pointed out by Professor W. M. Davis, may spread out a mile or more in breadth and a foot or two deep.

Some of the drainage-courses in Australia in dry seasons present no evidence of a definite channel.

Periodic rains on mountains, as in the case of the Nile, cause floods at fairly regular intervals. In the Sahara Desert the dry water-courses, or Wadies, like the Creeks in Australia, may receive water very suddenly after heavy rain in distant mountainous regions.

Floods due to long-continued rainfall may raise a river as much as 20 feet or more above its ordinary level. At such times, as at Norwich, the overflow from mill-streams has served to increase floods in adjacent lowlands. In the recent Paris floods (January, 1910), the Seine was raised about 21 feet about its normal level.

The blocking of a stream by ice, landslip, or the rapid thaw of snow on hard frozen ground, may likewise lead to floods. Quite recently the Falls of Niagara were dangerously choked with ice.

The effects of land drainage appear to vary in different areas. Thus, Mr. J. Bailey Denton was of opinion that well-drained and cultivated land with free soils gave more capacity for the reception of rain, so that the rainfall was discharged more gradually, and surface freshets became less common.¹ The Rev. J. C. Clutterbuck, however, remarked that floods in the Thames near Abingdon, which formerly reached their highest point in seventy-two hours, in 1862 reached that point in about thirty-six hours, owing to the increase in agricultural drainage.²

¹ *Proc. Inst. Civ. Eng.*, xxi., 1862, p. 48.

² *Idem*, xxii., 1863, p. 336; see also A. R. Binnie, 'Report on the Flow of the River Thames' (*London County Council*), 1892.

The Cherwell is regarded as one of the chief sources of flood-water near Oxford; it drains a large area of clay-country, and therefore the waters rise rapidly after heavy rain.

The higher courses of rivers are usually clear, except in times of flood or spate; in the lower courses much more sediment is usually present. High tides, aided by winds, dam up the water in the Thames estuary, and cause floods along the lower course of the river valley.

Reference has been made to Red rivers (p. 14) that convey ferruginous matters. In Cornwall there are also White streams which convey the washings from the China clay works, and near St. Austell appear like rivers of milk. Mansergh (1882) has also referred to black, red, or yellow streams in the manufacturing and mining districts of the north of England. Near Chesterfield black water is due to processes of coal-washing. (See p. 285.)

It was remarked by Prestwich (1851) that in many cases 'streams and rivers may be considered as representing, in definite lines on the surface, a water-flow agreeing in its general direction with that which takes place bodily in the strata below.' The remark naturally applies to those instances where pervious strata underlie the river channel. Thus, underground flow may take place in Chalk, and more freely in Carboniferous Limestone or Valley gravels, if there is sufficient fall in the land and an outlet for the water at lower levels.

Mr. Slichter (1902) has drawn attention to the fact that ground-water flowing towards a river may take a general direction down the natural water-course, or (as he terms it) the 'thalweg,' towards the sea, constituting

a considerable underground, if sluggish, flow, more or less independent of the surface flow. This underflow would naturally be affected by the depth of the channel and the coarse or fine nature of the strata. The subject is of importance in connection with supplies of water obtained from Valley gravels and subjacent pervious strata.

Bordering permeable strata, moreover, may receive much water by infiltration from such sources, although, as remarked by E. A. Smith (1907), the pressure along the sides of a river-course may not equal that exerted by bordering land - water. Much depends on the question of abstraction of water by wells. If a stream has clayed its course, the underground flow or subterranean 'thalweg' will not be directly connected with the superficial flow.

In the case of the Nile Valley near Cairo, Mr. A. Lucas has pointed out that all the wells near the river, including one 460 metres away, 'showed a rise in water-level immediately following the rise in the Nile, but beyond a certain distance from the river, the time taken for the influence of the Nile flood to reach the wells is no longer in strict proportion to the distance travelled; thus, the well 2,650 metres from the Nile showed a rise in water-level six days before any rise was found in a well only 800 metres away. Evidently other factors, such as the composition of the underground strata, are responsible for these apparently erratic results.'¹

Some streams and rivers lose a good deal of water along their courses when they traverse the outcrop of porous strata, such as sandstones or limestones, when the plane of saturation is low, and there is escape from

¹ *Cairo Scientific Journal*, ii., 1908, p. 311.

the strata at a distant lower level by natural exit, or water is abstracted by pumping.

As noted by J. H. Taunton (1887), the Churn, a tributary of the Thames between Colesbourne and North Cerney, a distance of four miles, lost in the Inferior Oolite and in the Great Oolite nearly $2\frac{1}{2}$ million gallons a day, according to gaugings in October, 1859. Much of this water reappears in the Boxwell springs, which arise at South Cerney, and yield from a million to 2 million or more gallons a day. They issue from a fault-fissure, where the Forest Marble and Great Oolite are brought against the Oxford Clay.

Underground flow is thus modified by changes in the strata, whether by natural succession or by faulting.

Among the streams which in seasons of drought disappear for a space and leave their courses dry is the familiar instance of the Mole in Surrey, which, as its name implies, dives underground, or loses a part of its water in the Chalk when the plane of saturation is low. The Loose, a tributary of the Medway, disappears at several places along its course in the Hythe Beds, as pointed out by Mr. F. J. Bennett.¹

The River Manifold, in North Staffordshire, is another well-known example. As remarked by Ansted (1878), 'The course of the river is through the [Carboniferous] limestone in the romantic valley of Welton, remarkable for its fine natural caverns. In this part of its course the river disappears for six miles, passing through an underground channel, and emerging at Ilam. While thus submerged, its course is indicated in the valley.'

The Echo River of the Mammoth Cave in Kentucky

¹ *Geograph. Journ.*, September, 1908, p. 286.

is stated to be from 20 to 200 feet wide, and 10 to 40 feet deep.

In Central Australia there are rivers that lose so much by percolation, as well as evaporation, that they disappear, or terminate inland in marshy expanses of saline water.

Swallow-holes, known also as 'swallet-' or 'sink-holes,' are natural openings and channels, more or less funnel-shaped, and formed or enlarged by the action of water holding carbonic acid gas in solution, on permeable and fissured strata such as Chalk and other limestones, notably the Carboniferous Limestone. Through these openings springs and streams are diverted underground.

Swallow-holes occur in characteristic form along the Mendip range in Somerset, at the junction of the Carboniferous Limestone and underlying Lower Limestone Shales. The strata occur in the form of a denuded anticline. (See Fig. 16.) The Old Red Sandstone, A, locally forms the highest ground, and springs issue from joints and disintegrated conglomerates in that formation, being thrown out by the lip of overlying Lower Limestone Shales at points where crosses are marked. After traversing the lower ground formed by the shale-outcrop B, the streams disappear in swallow-holes, where circles are marked, through the bordering Car-



FIG. 16.—SPRINGS ALONG ANTICLINE OF THE MENDIP HILLS.

boniferous Limestone, C, which rises in places above the level of the Shales. Through fissures, joints, and caverns, the water descends in the Limestone, flowing towards the flanking beds of Dolomitic Conglomerate, D, a formation usually much jointed, and springs issue at the junction with the overlying Keuper Marls, E.

Thus from swallow-holes near Priddy the water finds an exit near Wookey Hole. At Priddy much lead-ore has from time to time been obtained, and some years ago pollution of the water at the Wookey Hole paper-mill led to an action at the Court of Queen's Bench—the owner of the mill being held to be entitled to protection from the pollution of the water due to the lead-washing processes. Another spring descends a swallow-hole near Charterhouse, on Mendip, and issues below the Cheddar Cliffs.

In Derbyshire, south-west of Castleton, Elden Hole has been described as a bottomless pit, and was noticed in a work on 'The Hundred Wonders of the World.' The base, however, has been ascertained to be about 200 feet from the surface.

In the Craven District about Skipton in West Yorkshire, there are numerous swallow-holes or sinks, and the underground courses of several streams have been very carefully investigated.

Malham Tarn in north-west Yorkshire rests on inclined Silurian rocks, bordered on the north by the Carboniferous Limestone, from which issue springs that supply its water. The outflow from the Tarn is on the south, and the water, after crossing the Silurian outcrop, sinks into the Carboniferous Limestone that is brought abruptly against the older rocks by the North

Craven fault. The waters disappear in several swallow-holes.

To the south-west of Malham Tarn there is a stream which disappears in a swallow-hole at Smelt Mill; while to the east and south-east lies Gordale, along which also water passes underground in the Limestone.

To determine the respective points of issue of these underground waters was a task undertaken by the Yorkshire Geological and Polytechnic Society in 1899, with the aid of various chemical tests. (See p. 72.)

The conclusions of the Committee were—

1. That Malham Cove Spring discharges the water from Smelt Mill Sink and the limestone area west of the dry valley, and under certain conditions some of the Tarn water.
2. That Aire Head Springs discharge the main portion of the water disappearing down Malham Tarn Water Sinks.
3. That Gordale Beck Springs discharge the water sinking in Upper Gordale.

The investigations show that within the area the main direction of underground flow is along the master-joints of the limestone.¹

Subsequent investigations were made by the same Society on the underground waters of Ingleborough. The conclusions, drawn up by Mr. Arthur R. Dwerryhouse, were that the flow of the underground waters of the area was radially outwards from the high ground, but was profoundly affected by the direction of the joints in the Carboniferous Limestone. Moreover, it

¹ The complete report, edited by the Rev. W. Lower Carter and Mr. W. Cash, and fully illustrated, was published in the *Proc. Yorkshire Geol. and Polytechnic Soc.*, xiv., Part I., 1900.

was evident that the irregularities in the floor of Silurian and Ordovician rocks beneath the Limestone formed underground watersheds, which determine or modify the direction of flow. It was noted that the joints in the Limestone usually passed through one bed only, and not through the mass of the formation; but sometimes they extended to the base, and in this case they appear to be due to faults. The influence of the joints on the direction of underground flow was stated to be so strong that in several instances streams were carried beneath a surface watershed, and emerged in a different drainage basin from that in which they originated.

In both the Malham and Ingleborough districts some streams were found to cross each other during their subterranean courses, and others to pass beneath those on the surface of the ground.¹

In the Lincolnshire Limestone at Benefield, Northamptonshire, there is a stream which disappears at times in swallow-holes, and this is the case elsewhere in the county, as at Grimsthorpe. Swallow-holes are also met with in the Magnesian Limestone, as near Ripon.

In Chalk districts swallow-holes usually occur near the junction with the Eocene strata (Reading beds, etc.). They were formed, as Mr. Whitaker has remarked, by streams flowing over the more or less impervious Eocene strata, until they reached the pervious and jointed Chalk, into which they gradually sank, and in time, both by chemical and mechanical action, eroded the funnel-shaped hollows.

Very fine examples of swallow-holes, described by the Rev. O. Fisher, occur on the heath-lands of Affpuddle

¹ *Proc. Yorkshire Geol. and Polytechnic Soc.*, xv., 1904, pp. 248, 291.

and Puddletown, near Dorchester, at an elevation of nearly 500 feet above the sea. They mostly vary from 60 to 80 yards in circumference, but one known as 'Culpepper's Dish' is 290 yards round, and its sloping sides measure 47 yards.

Near North and South Mimms, in Hertfordshire, there is a series of swallow-holes in the Chalk which receive the drainage of the Colne from about twenty square miles of country. When the plane of saturation is low the stream disappears, and while much of the water goes in a northerly direction, it has been considered likely that some may travel eastwards to the springs of Chadwell and Amwell.¹

Many swallow-holes have been observed by Mr. F. J. Bennett in the Hythe Beds (Kentish Rag) near Maidstone, notably in the drainage area of the River Loose, some in the valley-bottoms, others on the water-partings.² He has attributed the formation of certain swallow-holes to the uprising of water, during the erosion of the valley, water under artesian pressure being liberated after the removal of overlying impervious strata. It would be advisable to apply some other name than swallow-holes to cavities formed from below. In the Midland Valley of Scotland the term 'Sit' is applied to a hole or hollow formed by the falling in of caverns.

From the foregoing remarks it will be understood that the underground courses of streams that are engulfed in swallow-holes cannot in many cases be determined by natural evidence, and recourse has been had

¹ W. Whitaker, 'Geology of London,' *Mem. Geol. Survey*, vol. i., 1889, p. 203; J. Hopkinson, 'Geology in the Field,' Jubilee vol. of *Geol. Assoc.*, Part I., 1909, p. 11.

² See 'Ightham: the Story of a Kentish Village,' 1907.

to various salts and colouring matters, by the introduction of which the directions of some underground waters, like those in the Craven district, have been proved. The substances used for the purpose include lithia (minute quantities of which can be detected by spectrum analysis), lithium sulphate, sodium chloride, ammonium chloride, and fluorescein (a dye). By the use of an electrolyte, such as ammonium chloride, the passage of water containing it can be indicated by an electric method. These tests have been employed in questions where the proof of a defined channel of water was required.

‘**Pipes,**’ ‘**Sand-pipes,**’ or ‘**Pot-holes,**’ in the Chalk, filled with sand, gravel, and clay-with-flints, are common features on the down-lands, and, like swallow-holes, are due to local dissolution of the limestone rock. They are formed well above the plane of saturation, and sometimes cause subsidences of the ground. As remarked by Mr. Whitaker, ‘Some pipes may at one time have been swallow-holes.’ They were regarded by Prestwich as extinct natural water-conduits.¹ Extending irregularly in a more or less circular form, over an area of many square yards, they soon diminish downwards in size, but may extend to considerable depths. The channels cut the Chalk often at an angle, and are sometimes penetrated in wells at a depth of 100 feet or more, ferruginous earthy matter being thus introduced into the water.

The term ‘pot-hole’ is sometimes applied to swallow-holes or enlarged joints in the Carboniferous Limestone.

¹ ‘Geology of London,’ vol. i., 1889, p. 124; Prestwich, *Phil. Trans.*, 1864, p. 300; *Quart. Journ. Geol. Soc.*, xi., 1855, p. 80.

While certain rivers and streams lose in bulk through percolation into subjacent porous strata, in many cases they receive springs which rise from the bottom or margin of their courses.

In some cases this has been due to the liberation of water pent up beneath an impervious floor which was eroded by river action, an explanation suggested in 1894 by Captain H. G. Lyons, and advocated by Mr. F. J. Bennett, in reference to the origin of the Loose Valley in Kent. Usually the springs simply mark the level of the plane of saturation in the bordering rocks, and they issue freely along lines of fissure, rising sometimes from small conical hollows due to erosion.

In a pool near Watford, about 16 feet deep, known as Otterspool, springs rise at the bottom, and yield an amount estimated by Mr. J. Hopkinson at from 300,000 to 1,000,000 gallons a day.

Another spring near Leatherhead, noted by Mr. J. W. Grover, rises from a hollow in the bed of a mill-pond, and yields at times more than 3,000,000 gallons a day, the water having a fall of about 11 feet into the River Mole.

The Chadwell spring is considered to rise from a fissure in the Chalk, and the outlet is an inverted cone about 18 feet deep. (See p. 71.)

Bournes.—The term ‘bourne,’ which means a stream, rivulet, or burn, is applied to the spots whence springs issue and streams take their rise after long-continued rain, and at higher positions in a valley than the ordinary source. They rise, in fact, at long intervals in some otherwise dry valleys, and more regularly in other cases. They are thus known as Intermittent Streams. Bournes are common in Chalk valleys and in other

limestone valleys, where the conditions favour a gradual rise in the water-table, and they are simply due to the increased height of the plane of saturation.

The Thames Head at Trewsbury Mead, north of Kemble in Gloucestershire, is a bourne in the Great Oolite, but only occasionally does the water issue at that spot; the flow has been considerably diminished by pumping from wells, and the usual source, as noted by Professor E. Kinch, is half a mile south of Acman Street, below the pumping-station for the Thames and Severn Canal, and sometimes it is four miles below the nominal head. In some places, where the brooks commonly issue at the higher level in winter, the name Winterbourne is applied, as in the Chalk districts of Wiltshire and Dorset. In such tracts the higher courses of stream valleys become dry in summer-time, and many of the dipping-wells fail to yield water, as at North Tidworth on Salisbury Plain; at other times the water in the wells overflows.

In Kent the term Nailbourne, in Sussex the term Lavant, and in Yorkshire that of Gypseys, is applied to similar intermittent Chalk streams.

In Hampshire, as pointed out by Mr. H. J. Osborne White, a branch of the Itchen rises at long intervals to the south of Axford and Nutley, but melting snow sometimes causes floods when the stream is not flowing.¹

The Croydon Bourne is the best known example, as its rise from time to time has caused considerable inconvenience, and gardens that have been laid out across what appeared to be a dry valley have been intersected by a running stream.

The uprising is indicated in diagrammatic form in

¹ 'Geology of Basingstoke,' *Mem. Geol. Survey*, 1909, p. 105

Figs. 17 and 18, the former based on an illustration published by Messrs. T. C. Chamberlin and R. D. Salisbury.¹ The continuous curved lines in Fig. 17 indicate the form of the ground; looking up the valley, the broken lines A and B indicate different levels in the

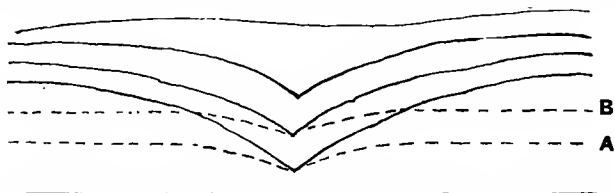


FIG. 17.—DIAGRAM ILLUSTRATING THE RISE OF A BOURNE :
TRANSVERSE SECTION.

plane of saturation of the Chalk, whereby the Bourne issues higher up the valley when the water-table rises. A and B in Fig. 18 show the rise of water in longitudinal section.

In the winter of 1903-04 the Croydon Bourne

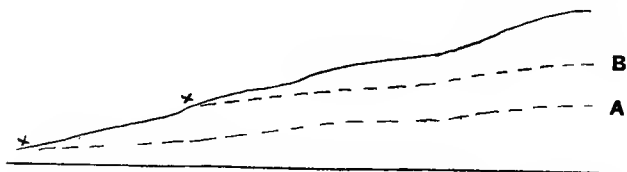


FIG. 18.—DIAGRAM ILLUSTRATING THE RISE OF A BOURNE :
LONGITUDINAL SECTION.

broke out, the highest point reached being at Bughall Farm, about half a mile north of Woldingham Station. It appeared first a little below the Rose and Crown, Coulsdon, gradually rising higher and higher in the valley.²

¹ 'Geology,' vol. i.: 'Processes and their Results,' 1905, p. 68.

² W. Whitaker, *Proc. Geol. Assoc.*, xviii., 1904, p. 388.

The outbreak was predicted by Mr. Baldwin Latham from observations on the gradual rise in the water-level of adjacent wells. He remarked (1904) that 'it is the rain that falls immediately preceding a Bourne flow which really governs its future appearance and volume.'

From October to March, 1903-04, the rainfall was a trifle over 18 inches, nearly 5½ inches falling in October. Mr. Latham further observed that, 'Owing to the very much larger amount of rain which falls on the higher district, and its less liability to waste, it has been found that the water in the deep wells in the higher parts of the district always begins to rise before the water in the wells in the lower part of the district. This may appear rather curious to some persons, that the top of the basin should begin to fill before the bottom; but when it is considered that a much larger amount of water percolates into the ground in the higher district, and that there is considerable resistance offered by the strata to the water flowing rapidly away from the upper part of the basin, it is sufficient to account for what really occurs, which enables the Bourne flow to be predicted some considerable time before it breaks out.'

The Croydon Bourne has again been flowing in March and April, 1910. On March 21, the flow below the Rose and Crown was ascertained by Mr. Latham to be 2,305,890 gallons per day. Another Bourne was also flowing at Stoa's Nest, Marlpit Lane, near Purley.

Owing to the pumping of water on an extensive scale, the saturation-level has been permanently lowered in certain areas, and the uprising of Bournes has become less frequent and less extensive.

In Hertfordshire, for instance, the plane of saturation

is being unduly lowered by pumping, as shown by the diminished outflow of the Chadwell spring near Ware.¹ Mr. Hopkinson has mentioned that the Hertfordshire Bourne, which rises between Berkhamsted and Boxmoor, has only once been known to flow when the mean rainfall in the county for the year ending March 31 has been less than 30 inches.

The large quantities of water pumped from the Chalk of Kent have likewise affected the flow of the Cray.

There is no doubt, therefore, that the pumping of water from wells is so much lost to the springs and rivers. It cannot always be determined that the amount taken is abstracted from a particular drainage area. The bulk may be returned to the land or river in the form of sewage, but it is not unfrequently the case that the water is taken from one river-basin and transferred to another. This is also the case with some impounding reservoirs where water is conveyed in pipes from one drainage area to another.

Dumb-wells, Absorbing or Blind wells, sunk through impervious strata into porous rocks beneath, have sometimes been made to carry off land-drainage, as in Lincolnshire, through the Upper Estuarine clays into the Lincolnshire Limestone. In agricultural districts pollution of underground waters may thus be caused.

During the past thirty years suggestions have been made for the construction of 'dumb-wells' or 'inlet drains,' into porous strata, to prevent some of the 'unproductive rainfall passing to the sea,' thus alleviating floods and equalizing the flow of rivers, and at the same time replacing stores of underground water

¹ J. Hopkinson, art. 'Geology' in 'Victoria History of Hertfordshire,' vol. i., p. 29.

where pumping has seriously diminished the amount.¹ Mr. Beeby Thompson proposed that dumb-wells be carried through the Alluvium and Upper Lias into the porous beds of the Middle Lias, near Northampton, so as to conduct underground a portion of the surface-waters from the Nene Valley—a project that would lessen the floods and restore the depleted underground waters.²

Mr. George Barrow has recently suggested to the writer that the underground supply in the Chalk of the London Basin might be maintained by means of dumb-wells sunk into the Chalk through the London Clay, etc., and fed by stored and filtered river-water. In his opinion the underground water might be also augmented by excavations in the Chalk area, allowing the rainfall to freely enter into the strata ; or by conducting water into the swallow-holes of North and South Mimms.

The natural storage of water in excavations made in porous strata has been put in practice in India and other regions. (See also pp. 123, 148.)

These sources are sometimes termed 'Abstraction Reservoirs.'

¹ E. Easton, *Rep. Brit. Assoc. for 1878*, p. 684 ; C. E. De Rance, *Internat. Health Exhib.*, Conference, July 24, 1884.

² 'Middle Lias of Northamptonshire,' 1889.

CHAPTER VI

SPRINGS

THE rainfall naturally tends to fill up all the pores, cavities, chinks, and crevices, of the rocks which appear at the earth's surface, until the more porous and fissured strata are so saturated that the additional water from rainfall overflows in the form of Springs.

Their mode of occurrence is regulated by the geological structure, and thereby we find an infinite variety of land-springs, near the surface, from the subsoil or substrata, and deeper-seated springs on the slopes of mountain and hill, and along the low margins of some valleys. Their issue depends on the alternations of permeable or jointed and impermeable strata. They are the outlets of underground streams that in some instances may have fairly defined channels over an impervious floor, while in other cases they flow through joints, fault-fissures, or caverns.

Sometimes only feeble flows occur in many places along a scarp; the water, in fact, weeps out in the form called 'seepage.' In such cases conduits may be constructed to gather the water.

An ordinary hillside spring is formed when sand and gravel, sandstone, limestone, or other porous strata, rest upon an impervious bed, as in Fig. 19.

Here the supply in the gravel B is liable to fail

in times of drought, because, with the gentle inclination of the impervious bed of clay A, springs would be given out only on one side of the hill, where the cross is marked.

Irregularities in the clay floor (as in Fig. 11, p. 53) serve to store up water, and in consequence a well at one spot may continue to be productive when an



FIG. 19.—OUTLET OF SPRING ON INCLINED STRATA.

adjacent well has failed. Wells carried a few feet into the clay will have the advantage of storing up supplies.

Where the impervious floor is essentially flat, as exemplified in the Middle Lias outlier of Pennard Hill, near Glastonbury, the surplus water escapes mostly in the form of seepage all round the hill, concentrated only in a few places in springs that are not very copious.



FIG. 20.—ORDINARY OVERFLOW SPRING.

Inclined strata, with an inward dip from the hill-slope, will store more water than similar strata in a horizontal position. See Fig. 20, where the water-table in sandstone is shown by a broken line, a spring is marked by a cross, and clays occur above and below the sandstone.

In some cases, as in the Cotteswold Hills, there may be three horizons of springs in succession, the higher

issuing from the Great Oolite based on the Fuller's Earth clay, the middle from the Inferior Oolite and Sands based on the Upper Lias clay, the lower from the Middle Lias rock-bed (Marlstone, etc.) based on underlying Middle Lias clays.

In Fig. 21 three sets of springs, marked by crosses, are represented. Under certain conditions the waters from the limestone D, the higher spring on the scarp, may enter the outcrop of the lower limestone B, over the outcrop of the shale C, as was noted in reference to Fig. 8, p. 28. Owing to the inclination of the strata, rainfall on the outlier of sand F issues in the form of a spring at the point marked by the cross, and a stream flowing along the dip-slope may pass underground beneath the sand on the right hand of the section. A, C, and E, represent clays.

Very copious springs issue in places from the Oolites. Thus, at Bourne in Lincolnshire rather more than $4\frac{1}{2}$ million gallons a day issued from springs at Well-head. Probably the amount is now much reduced by the pumping from various wells in the district.

In Oolitic regions on the north



FIG. 21.—SPRINGS ALONG SCARP AND DIP-SLOPE.

side of the Thames, it was calculated that 70 million gallons a day were yielded by a dozen springs.¹

In all districts of the Carboniferous Limestone copious springs are met with.

In situations where the strata are inclined, two sets of springs may naturally issue from the same formation, the one below the scarp, the other on the dip-slope, if the water-bearing stratum be partially covered as well as underlaid by impervious layers. The geological structure is shown in Fig. 22, and the crosses indicate the springs. A somewhat similar structure was illustrated in Fig. 12, p. 55.

Springs of this nature may be of a more permanent character than the ordinary springs before mentioned ;

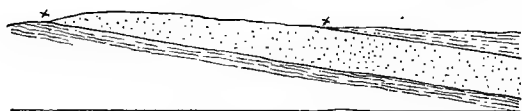


FIG. 22.—SPRINGS AND UNDERGROUND FLOW OF WATER.

some, in fact, are perennial. In such cases, and especially below a scarp, the outlet becomes gradually deepened by erosion of the lip of clay, and the springs in consequence issue at a few feet below the general line of junction. By erosion the underground channel may be accentuated on the concealed drainage area, when the strata are not highly inclined.

Many springs actually issue at a still lower level by reason of talus or débris from the scarp, and sometimes from the effect of larger tumbled masses or landslips. This is shown in Fig. 23, where the natural outlet of the spring would be at the junction of the limestone B

¹ *Sixth Rep. Rivers Pollution Com.*, 1874, p. 297.

with the shale A, whereas the spring appears at the surface below the tumbled rocks at the point marked by the cross.

In collecting water from such sources, it is necessary to open up the spring at its fountain-head, and supplies may be increased by deepening the natural outlet.

In mountainous regions formed of hard impervious rocks with great scree, copious springs may issue at the foot.

Along the cliffs near Lyme Regis a slight seaward dip of the strata favours the outflow of springs, and

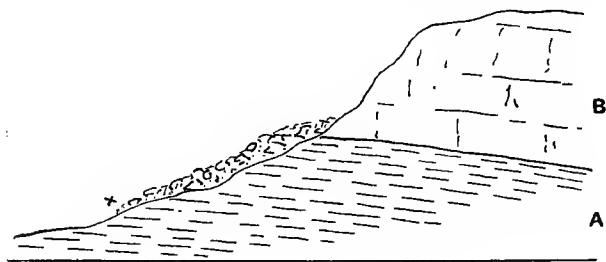


FIG. 23.—OUTLET OF SPRING OBSCURED BY DÉBRIS.

tends to the production of landslips owing to the weakening of the foundation of Upper Greensand below the Chalk.

In basins, as in steeply inclined strata (see Figs. 8 and 34), the surplus rain that falls upon the saturated porous beds must overflow, unless underground water is abstracted by wells.

Faults very naturally afford facilities for the transmission and escape of water, especially when they affect hard rocks, or bring porous strata against impervious, as exemplified in Fig. 25, p. 86.

They likewise in some cases afford means of circu-

lation through impervious strata. In the Kimeridge Clay or shale of the Dorset coast, many springs are seen to issue along planes of dislocation.

Again, springs of an artesian nature have been able to issue from the Lias clays, as at Cheltenham, probably through faults. At a depth such clays are compact and hard, and a slight deposition of mineral matter along joints and fault-planes may facilitate the upward passage of water by keeping open the fissures.

An instance was met with in Somerset, where a copious spring issued from what appeared to be impervious marls. They were, however, faulted against water-bearing Lias limestones, and the ground-water,

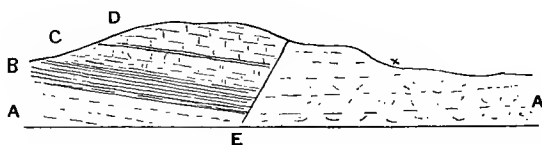


FIG. 24.—SPRING ISSUING FROM FAULTED CLAYEY STRATA.

having at a former time risen along the fault-plane, had cut a narrow ravine in the marls which was partly choked, but sufficiently open for the spring to find free exit at the point marked by the cross.

In the section, Fig. 24, A represents marls, B shales, C and D White and Blue Lias limestones, and E the Fault.

Hard bands in argillaceous strata may occasionally throw out springs with a remarkable amount of water. In the Keuper Marls of Somerset, near Pilton, such a spring was suggested as likely to furnish a useful water-supply. It escaped from a hill-slope at some distance above an adjacent stream. On following up

the stream, it was found that shelving masses of hard rock occurred along its course, with a strike towards the spring. The stream, much polluted by adjacent farm premises, lost a good deal of water along the belt of hard rock, and this escaped lower down in the hillside spring.

In hard sandstones and grits, and also in hard limestones, springs issue from joints and fissures above bands of shale or clay, notably in the Millstone Grit and in some of the Lower Carboniferous rocks of Derbyshire and northern countries. Where the gathering ground is not large, springs from such sources are more liable to fail in times of drought than those from more porous strata, such as the Oolites and Chalk.

Again, a hard Iron-pan, formed of gravel or sand cemented by ferruginous matter, or similar beds cemented by siliceous or calcareous matter, may arrest percolation in the midst of porous strata.

Springs will issue where hard rocks, including granites and other crystalline rocks, much fissured or decomposed, arise from the midst of an overlying clay or slate formation, such as the Keuper Marls or the Devonian slates. Springs from the Malvern Hills—the Holy Well at Malvern Wells and St. Ann's Well at Great Malvern—issue from the surface portions of the old crystalline rocks at their junction with Keuper Marls; others from granite masses in Cornwall and Devon are due to the overflow caused by surrounding slaty rocks.

In some cases it is difficult to determine whether the water is simply dammed up in the shattered and fissured surfaces of old rocks, or whether it rises along a fault-plane under a certain amount of artesian pressure, as in Fig. 25.

There the spring marked by a cross may be fed from both sources. C represents hard impervious rock, the weathered and shattered portions of which would yield some supply of water; while the outcrops of the permeable sandstones B, between the shales A, would take in a certain amount of the rainfall, and the water, dammed up against the impervious rock, would rise by artesian pressure to feed the spring.

Holy Wells, dedicated in most cases to a saint, are met with in all parts of the world.¹ In this country they are frequently situated in proximity to a Church or Abbey, often actually draining from the burial-

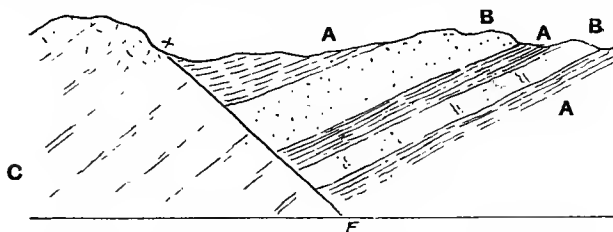


FIG. 25.—ARTESIAN WATER DEPENDENT ON FAULT.

grounds; and it is not surprising that their virtues in some localities, as at Glastonbury, have been attributed to their passing over the graves of holy men.

St. Winifred's Well, Holywell in Flintshire, is fed by a copious spring from the Carboniferous Limestone. Holy water from the Prophet's Holy Well at Mecca is supplied in metal flasks to pilgrims, and used in small quantities as a remedy for various ailments.

The name of Seven Wells or Springs is met with in several localities, as on the Cotteswold Hills, at the

¹ R. C. Hope, 'The Legendary Lore of the Holy Wells of England,' 1893.

occasional source of the Churn at Cubberley, and in several localities elsewhere.

At Tissington in Derbyshire there are 'five never-failing springs,' and there the old custom of 'well-dressing' is observed on Ascension Day.

Wishing Wells, of which an example is met with at Upway, near Weymouth, may possibly derive their name from the Keltic word for water, exemplified in Wisbech, Wishford, etc.

Names of places often indicate the presence of prominent springs, as in the case of the city of Wells in Somerset, Wells in Norfolk, Amwell, Bakewell, Tunbridge Wells,¹ Bourne in Lincolnshire, etc.

An examination of a geological map, such as that on a scale of four miles to one inch, indicates how the situation of many villages and towns was governed by the outcrop of water-bearing strata, the original settlements being made at or near the sites of prominent springs.

Changes in atmospheric pressure, as remarked by Mr. Baldwin Latham (1881), influence the level of the water-table and the flow of springs. With a fall in the barometer he finds the flow of springs and of water in wells to increase, and with a rise in the barometer the flow of water diminishes. The increased air pressure in the strata impedes the circulation of water.

Blowing Wells occur in all parts of the world, but only occasionally attract special attention, when accompanied by a trumpeting sound.

They may be caused by a rapid rise in the ground-

¹ The suffix *well* in many cases is a corruption of *ville*.

water level or water-table, which drives the air out of the porous or fissured strata ; or they may be due, as noted by Dr. A. Strahan¹ and by Slichter (1902), to a 'low barometer,' whereby quantities of air may escape sometimes with a roaring noise. In the same way the escape of fire-damp (carburetted hydrogen) or of choke-damp (carbon dioxide) in coal-mines, and offensive odours from sewers, are greatly influenced by diminished atmospheric pressure.

Mr. Beeby Thompson has remarked that 'The Drumming Well' at Oundle, in Northamptonshire, which was sometimes silent for years, no doubt owed its peculiar characteristics to the forcing of air out of crevices by rising water, or possibly by indraught caused by a lowering of the water-level.²

Some blowing wells have been noted at Framingham, near Norwich, by Dr. S. H. Long. In one instance an iron covering had been blown off.³ The fluctuations in water-level are probably the cause of the blowing out of air, as I am informed by Mr. F. W. Harmer.

Bubbling or 'boiling' springs are due to the amount of aeration and the escape of gases. Some throw up sand. At Billingborough in Lincolnshire there is a strong spring, which, as stated by Mr. W. H. Dalton, is in a state of constant ebullition, due to the evolution mainly of nitrogen, but also of minor quantities of oxygen and carbonic acid. The name of the village is said to be a corruption of 'Boilingborough.'

Minor fluctuations in the water-level of wells have

¹ 'The Movement of Air in Fissures and the Barometer,' *Nature*, February 15, 1883, p. 375.

² *Ibid.*, June 10, 1909, p. 429.

³ *Ibid.*, May 20, 1909, p. 339.

been attributed to the pressure of gases, such as carbonic acid gas. Wells of this kind are sometimes termed Pulsating Wells.

In the sinking of wells to a considerable depth provision for ventilation is necessary.

The carbonic acid gas given off in respiration by the workmen, the evolution of gas from the strata, and that produced by blasting combined with injurious stone-dust, require attention.

Carbonic acid gas has been given off from the Chalk and other strata, with fatal effects in some cases.¹

Sulphuretted hydrogen due to the decomposition of iron-pyrites has been encountered in sinkings in clays, such as the Lias, the London Clay, etc., and in impure estuarine sands, and cases of suffocation from it have occurred.

The term '**Blow-wells**' has long been applied in East Lincolnshire to certain wells and springs the water of which rises naturally to the surface in the low lands. The water escapes when wells are sunk through Boulder clay or Alluvial drift into Chalk, in which the water is pent up. Some, as noted by Edward Bogg in 1816, overflowed 'with a greater flux at the time of high-water, and particularly at spring-tides.' Other wells are practically of an artesian nature.

Mr. C. Reid has remarked that between Grimsby and Little Coates there is a group of Blow-wells which have supplied Grimsby with water. 'They form several pools of clear water, which yield a supply sufficient for the town, though a great deal runs to waste.'² They

¹ See Dr. J. Mitchell, *Proc. Geol. Soc.*, iii., 1839, p. 151; also C. Le N. Foster and J. S. Haldane, 'The Investigation of Mine Air,' 1905.

² 'Geology of Holderness,' *Mem. Geol. Survey*, 1885, p. 128.

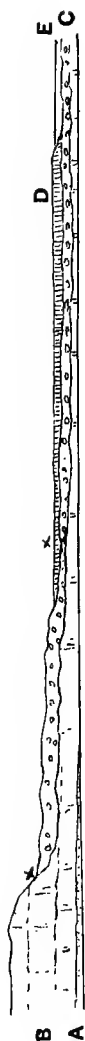


FIG. 26.—ARTESIAN WATER AND 'BLOW WELLS.'

appear to rise from a bed of gravel, which derives its water from the Chalk a mile or more distant, gravel underlying clayey drift being banked against the Chalk below the plane of saturation along an old buried cliff. (See Fig. 26.)

At Tetney there are Blow-wells which appear to rise directly from the Chalk, where it is covered in places with more than 60 feet of clayey drift, and they issue possibly along a line of buried valley excavated to the Chalk.

In Fig. 26 only a diagrammatic representation is given of the general structure of the ground bordering the north Lincolnshire marshlands. A represents the Lower Greensand (Carstone); B, the Chalk; C, Glacial Drift (Boulder Clay, Gravel, Sand); D, Alluvium; and E, the Sea. Where Boulder Clay, sometimes with underlying gravel and sand, abuts against the Chalk, springs are given out along the line marked by a cross on the left. Where the Glacial Drift is thin, or made up of gravel, springs may burst up through the Alluvium, from the pent-up water in the Chalk, as at the cross near the centre of the section.

Ebbing and Flowing Wells near Sea-Coast.—Outflows of springs may take place at intervals along the sea margin, the sea at high-tide acting as a dam and regulating the upper limit of the plane of saturation

in the bordering strata, fresh water gushing forth in springs at low-tide, from the base of cliffs, or filtering through Blown Sand and beach deposits. In fact, along a sloping sandy beach the plane of saturation by fresh water can be detected with a walking-stick a few inches beneath the dry surface of sand. Thus, the level of wells along estuaries and near the coast is often found to fluctuate with the tides, especially in Chalk districts, as near Eastbourne and at Rottingdean, and along the borders of the Lower Thames.

At Bridlington, a well made south of the harbour yielded no water at low-tide, but at about half-tide it commenced to flow, and continued to rise until the tide again fell to the low level.¹

A well with brackish water in the Carboniferous Limestone at the Flat Holm in the Bristol Channel is said to fill at ebb-tide, and to be empty at flow-tide.

At Newton Nottage, near Bridgend, there is an ancient dipping-well, slightly brackish, described by Mr. H. G. Madan as tapping water from the Dolomitic Conglomerate and Carboniferous Limestone. The bottom of the well is about 8 feet above Ordnance Datum, and is 500 yards distant from the shore at high-water mark. The water in the well continues to rise for three hours after high-water, and to sink for three hours after low-water. The influx of sea-water at high-tide takes place so slowly that fresh water rises before it has time to fill up the well.²

Attention has been called by Mr. A. Young to the occurrence near Cradock, in Cape Colony, of saline

¹ C. Reid, 'Geology of Holderness,' *Mem. Geol. Survey*, 1885 p. 129.

² *Quart. Journ. Geol. Soc.*, liv., 1898, p. 301.

water having a temperature of about 80° F. The water issues from four bore-holes, and 'rises and falls at twelve and a half hour intervals in a manner analogous to the oceanic tide;' and yet the locality is more than 100 miles distant from the sea-coast near Port Elizabeth, and the elevation is considerable.¹

Fresh-Water Springs at Sea.—It is well known that fresh-water springs rise in places at the surface through the heavier salt-water of the sea, notably along the coasts of the Mediterranean. Some were referred to by Greek and Roman philosophers, and Admiral Smyth gave particulars of many of them. Thus, on the east coast of Sicily, 'in the harbour of Syracuse, opposite the fountain of Arethusa, and probably from the same source, a copious spring of fresh-water rises from the bottom, without intermingling with the brine.' In Northern Italy, in the Gulf of Spezia, the rising of fresh-water produces 'a slight convexity on the surface'; and in Southern Italy, in the port of Taranto, fresh-water 'may be taken up without the least brackish mixture.' In Greece, in the Gulf of Argos, a body of fresh-water estimated to extend over an area of 50 feet in diameter, and to represent 'the exit of a subterranean river of some magnitude,' rises with sufficient force to form a convex surface.²

In many parts of Sicily and Calabria fresh-water is obtained in wells sunk in sand and shingle adjacent to the sea-coast.

In the West Indies, the Keys or Cays, which border

¹ Rogers and Du Toit, 'Geology of Cape Colony,' 2nd edit., 1909, p. 418.

² 'The Mediterranean: A Memoir, Physical, Historical, and Nautical,' 1854, p. 140, etc.

one-half the coast of Cuba, are coral or mangrove islets, which just rise above the sea, and are for the most part uninhabitable owing to the want of fresh-water.¹

Humboldt was informed 'that in the Bay of Xagua, to the east of the Jardinillos, fresh-water gushes up in several places from the bottom with such force as to prove dangerous for small canoes. Vessels sometimes take in supplies from them.'²

Mr. Baldwin-Wiseman has remarked (1909) that 'bubbling up in the muddy waters of the River Humber is a large volume of fresh clear water, known as the Hesse Whelps, running to waste from the chalk.'

These waters, of course, are due to artesian conditions. (See also p. 129).

Inland Ebbing and Flowing or Periodic Wells have been observed at Tideswell, east of Buxton, Chapel-en-le-Frith, north of Buxton, at Giggleswick, near Settle, and other places in the Carboniferous Limestone.

Such springs have been attributed to the outflow from caverns, when rain has raised the level of the water to a certain height. A diagram indicating the general nature of the features is given in Fig. 27. They may be due to outflows from caverns, or simply from the rise in level of the ground-water among the fissured strata.

A in the illustration indicates shale, and B the plane of saturation in the overlying limestone, when the spring

¹ R. T. Hill in Mill's 'International Geography,' 3rd edit., 1903, p. 793.

² 'Travels and Researches,' edited by W. Macgillivray, 1832 p. 306.

would issue from the hillside; C is a fissure leading into a cavern, originating along a plane of slight faulting. If the limestone were dense and not fissured, the spring would issue when the cavity was sufficiently filled with water that entered by the fissure.

The Fountain of Miracles, on the side of Galero, in the Ligurian Alps, is said to flow at intervals of about fifteen minutes.¹

Influence of Earthquakes on Springs.—Earthquakes have modified the flow of springs, temporarily or permanently, causing some to cease.

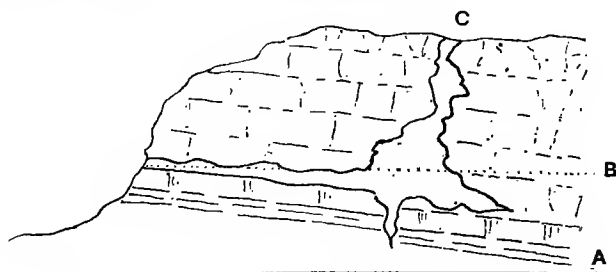


FIG. 27.—INTERMITTENT SPRING FROM CAVERN.

One result of the Essex earthquake of April 22, 1884, was to produce changes in the water-level of wells, and to affect certain springs.

At the Eagle Brewery, Colchester, in a Chalk well, the water-level, which had been 22 feet below the surface, rose 4 feet, and so continued for at least four months. At the Colchester Waterworks the water rose from 7 to $7\frac{1}{2}$ feet above ordinary level, and the height was maintained for about six months. At

¹ W. Parkinson, *Knowledge and Sci. News*, October, 1907, p. 225.

Bocking a rise of more than 18 inches was noticed. The shock, as suggested by C. E. De Rance, appears to have caused a widening of fissures in the Chalk, and a temporary increase in the flow. The waters ultimately returned to the original general level.

In some places the water in wells became turbid for a few hours, or even days, a spring became charged with reddish sand, and a few temporary springs were opened up. The water-tower at Colchester, with a tank capable of holding a quarter of a million gallons, was seen to oscillate, and it became slightly cracked. The most remarkable incident in connection with the effect on underground water was a turbidity noticed in the water derived from the Chalk, at a depth of about 600 feet, at the waterworks at Canterbury.¹

Red rivers or streams, carrying ferruginous mud, have been noticed to run in some regions after earthquake disturbances. (See also p. 14.)

¹ For the above particulars we are indebted to the 'Report on the East Anglian Earthquake of April 22, 1884,' by Professor R. Meldola and W. White (*Essex Field Club Special Memoirs*, vol. i., 1885, pp. 53, 75-77, 158-161).

CHAPTER VII

SURFACE SOURCES OF WATER-SUPPLY

IN previous chapters some particulars have been given of the natural distribution of waters on and under the surface of the land. Attention must now be given to the question of supplies for practical purposes. These are to be obtained from—

1. Surface sources :

Rain.

Springs.

Streams and rivers.

Ponds, dew-ponds, and lakes.

Reservoirs.

2. Underground sources :

Shallow and deep wells or borings of ordinary or artesian nature.

RAIN-WATER.

Rain-water stored in butts and tanks has been utilized in many parts of this country and abroad for drinking and washing purposes, where other sources of supply are not available or would be too costly.

As already noted (p. 12), rain-water is not free from impurities, organic and inorganic, and in the neighbourhood of manufacturing towns it is suitable only

for horticultural purposes. Elsewhere, when collected from the roofs of buildings, it is liable to be contaminated with soot and other forms of dust, vegetable débris, and impurities from birds, insects, etc. Hence some form of purification is necessary. This may be carried out by filtration, whereby all rain-water is aerated and improved; but the necessity for any filter-bed may sometimes be obviated by the use of the apparatus known as the Separator, which acts automatically and carries off the first flow of rain.¹ A strainer and settling tank may in some cases be desirable before the water is stored for use.

Rain-water collected from slate roofs is decidedly preferable to that from tiles or galvanized iron, while lead roofs should not be utilized for drinking-water. Rain-water can also be collected with advantage from specially prepared surfaces of concrete. An inch of rain will yield about $\frac{1}{2}$ gallon of water per square foot of horizontal area.

Mr. W. H. Wheeler has pointed out that in the Fenland, 'where the quantity of rain is small, there is yet a sufficient fall on every house in the course of the year, if properly husbanded, to yield a supply to the inmates. A cottage covers about 500 square feet of ground; the rain falling on the slated roof, supposing, it to amount to 22 inches a year, the average for Lincolnshire, would yield about 5,700 gallons, or a daily supply of $15\frac{1}{2}$ gallons.'² A less amount may be sufficient for domestic use in some cottages.

Dr. J. C. Thresh (1900) estimates that about half the

¹ See article by B. Wynand, *Pall Mall Gazette*, August 26, 1909.

² 'A History of the Fens of South Lincolnshire,' 2nd edit., 1894, p. 469.

amount of rainfall, allowing for evaporation and waste, may be reckoned to be available when taken direct, and stored in accordance with requirements.

Rain-water for household purposes is stored in underground cisterns constructed of stone, brickwork, slate, or concrete; sometimes in surface tanks of galvanized iron, but this material is not suited for rain-water in the vicinity of manufacturing towns, where the rain is apt to contain traces of sulphuric acid.

RAINFALL AND RUN-OFF.

The proportion of rainfall which finds its way to form springs, streams, and rivers—the ‘run-off,’ as it is commonly called—varies enormously in different regions and at different seasons. Not only has climate to be considered, but also geological structure, the nature and depth of soil, the absorbent properties of the underlying rocks, the form of the ground, and the extent to which it is covered with vegetation. Moreover, it is important to note the nature of the vegetation, whether woodland or pasture, and whether the ground is under tillage, with artificial drainage. Nor must the effects of the pumping of water from wells be neglected. Mr. Baldwin Latham (1909) remarked that the gaugings of Chalk streams indicate that the actual flow of water from the ground bears a less proportion to the rainfall than is indicated by the percolation gauges. Pumping may account for the difference.

It is not practicable to separate with accuracy the immediate or surface run-off from the ultimate run-off or stream-flow, which includes the flow of springs. Approximate estimates, as already noted, are based on

the amount of percolation, and these may be aided to some extent by the gauging of springs.

In particular areas the relation between run-off and rainfall appears to be fairly constant, and the average annual discharge of rivers has been estimated at from $\frac{1}{4}$ to $\frac{1}{3}$ of the rainfall. This would apply to the Thames at Staines and to the Seine at Paris.

It is, however, liable to vary, according to L. F. Vernon-Harcourt (1896), from 75 per cent. on impermeable strata to 15 per cent. on porous ground. In some parts of the Transvaal it is reckoned to be from 5 to 10 per cent., and elsewhere, indeed, the run-off may be as little as 3 per cent. or less of the rainfall, when streams enter a desert region and lose by percolation and evaporation. For the world in general the average run-off is reckoned at no more than $\frac{1}{5}$ of the rainfall.

SUPPLIES FROM SPRINGS, STREAMS, AND RIVERS.

In gauging springs, streams, and rivers, the work must be done by an engineer or trained assistant. The following particulars were given by L. F. Vernon-Harcourt (1896):

The *discharge* is the volume which passes a certain spot in a given unit of time, usually reckoned in cubic feet per minute or second. Gaugings may be taken by means of sluices or weirs.

The *slope* or *fall* of a river is the inclination of its water surface.

The *sectional area* is taken at right angles to the current, and is expressed in square feet.

The *mean velocity* is the average velocity of all the elements of the current. It is ascertained by means of surface and

subsurface floats in calm weather, and the time taken by them to traverse a measured distance. Sometimes a current-meter is employed.

It is important to ascertain the minimum or dry-weather flow, usually at the close of autumn in dry years; also the normal flows, and that during periods of flood; and it is desirable that records should extend over several years.

Statistics relating to many rivers in the British Islands have been made from time to time, but there is no complete record of the annual discharge and the relation to rainfall and geological structure. Joseph Lucas in 1878 urged the importance of a Hydrogeological Survey of England, but nearly thirty years elapsed before any systematic undertaking was projected.

A commencement was, however, made in 1906 by a committee under the superintendence of Dr. A. Strahan, and observations on the Exe and its tributaries, and on the Medway, are now being carried out.¹ Nevertheless a much more complete series of investigations for the whole country, such as that carried on in the United States, in France, and elsewhere, is required.

Water for household purposes is obtained from springs and brooks, and raised by means of water or hydraulic rams. In these and other cases it is desirable that the gathering ground above springs that are utilized should be kept in grass and safeguarded. The limitations will vary in different cases according to the shape of the ground, the geological structure, and the nature of the soil.

¹ 'Report of Progress in the Investigation of Rivers,' *Geograph. Journ.*, 1908, p. 310.

At the outlets of springs tanks are sometimes constructed for storage.

The quality of river-water is dependent, not only on the strata which constitute the drainage area, but on the artificial influences in the cultivation of the land, and the drainage of villages and towns that lie within the region.

As a rule, rivers which receive sewage do not furnish desirable sources of potable water. At the same time it is well known that the flowing water becomes more or less purified along the river course, if not subjected to further serious contamination; and modern processes carried out on sewage farms tend to render the effluents comparatively harmless.¹ (See p. 281.)

Water obtained from streams may in the higher courses be distributed by gravitation.

River supplies have usually to be pumped after undergoing clarifying processes by means of strainers, settling tanks, and filter-beds, the water being transferred to one or more pure-water basins or clear-water tanks, from which it is raised into the service reservoirs.

Storage reservoirs are desirable in many cases, so that the river-water be not taken during floods; in some cases they are of importance in retaining the otherwise wasted water. (See p. 103.)

Plymouth was supplied by Sir Francis Drake as early as 1591 with water from the western side of Dartmoor, conveyed in a leat or open channel from the Meavy (or Mew), a tributary of the Plym. Reservoirs have since been constructed for the supply of the town.

¹ See *Fifth Report of Royal Commission on Sewage Disposal*, 1908.

Of towns and cities which take their supply wholly or in part by intakes from rivers, London stands foremost. The first regular supply, apart from that taken by means of buckets, was drawn from the Thames at London Bridge in 1582.

The first Water Company, that of East London, was formed in 1669, and others were constituted at various dates up to 1845. All were amalgamated under the Metropolitan Water Board in 1904. Since 1855 no water has been withdrawn for Water Companies below Teddington.

To obtain 200 million gallons a day, as remarked by G. J. Symons in 1867, 'requires a river 30 feet wide by 10 feet deep, flowing continuously day and night at the rate of some two miles an hour.'

At the present date the Metropolitan Water Board require about 225 million gallons a day to supply a population estimated at nearly 7 millions.

Of this amount of water, it is estimated that about 57 per cent. is taken from the Thames, and the remainder from the New River, the Lea, and from sundry wells carried into the Chalk both north and south of the Thames.

The canal known as the New River, projected in 1609, and completed by Sir Hugh Myddelton in 1613, was originally constructed to take water from the springs at Amwell and Chadwell near Ware. The water was delivered by means of pipes of bored elm-wood, which extended over a length estimated at about 400 miles. During the years 1810-1820 they were replaced by iron pipes. The New River water at the present day is in part supplied by the Chadwell spring, largely supplemented by water from

Chalk wells, thus yielding more than 30 million gallons daily.

Large storage reservoirs for the supply of London have been constructed at Staines and elsewhere in the Thames Valley above London, and at Walthamstow and other places in the Lea Valley.

Adding the amount of water taken by the Water Companies, the average daily flow of the Thames at Teddington Weir during forty years, with a mean annual rainfall of $28\frac{1}{2}$ inches, was estimated at 1,350 million gallons. For a shorter period of twenty years it has been 1,110 million gallons. During the summer months, the average at the weir is reckoned at about 500 million gallons, and rarely it has been as low in seven consecutive days as 179 (the minimum being 154) million gallons. This exceptional flow took place in August, 1887, but only during nine days of that month was the flow less than 200 million gallons a day.¹ In flood-times the amount exceeds 7,500 million gallons per day, that quantity having been recorded at Windsor in 1875. Allowing for the abstraction of water by the Metropolitan Water Board, there remains an average of about 1,000 million gallons daily. It is stated that the total amount which the Board can take from the Thames under existing conditions is $228\frac{1}{2}$ million gallons per day, and that the maximum supply from other sources is about 120 million gallons, making a total of $348\frac{1}{2}$ million gallons per day. It is further estimated that by the year 1941 about 420 million gallons per day will be required. By the construction of further storage reservoirs, it may ultimately be possible to take as much as 450 million gallons from the Thames

¹ *App. Roy. Com. Metrop. Water-Supply*, 1893, p. 371.

drainage area. At present provision is being made for supply that will meet the demand until 1917.¹

It has been reckoned that the mean annual flow of the Thames above the intakes of the Metropolitan Water Board represents about 9·8 inches of rainfall in the Thames Basin, rather more than $\frac{1}{3}$ of the yearly supply. The loss by evaporation and absorption has been estimated at from 15 to 17 inches of the rainfall.

Mr. Baldwin-Wiseman (1907) has given the following mean annual data with regard to the area of the Thames Basin :

	Inches.	Per Cent. of Rainfall.
Rainfall (over whole of Thames Basin)	26·12	—
Run-off	7·74	29·6
Evaporation	15·02	57·5
Percolation	+ 3·36	+ 12·9

The run-off is here given as the average discharge over Teddington Weir (1883-1902), when, owing to lesser rainfall, the average flow was 1,110 million gallons daily.

Mr. Baldwin-Wiseman observes: 'It is interesting to note from the above that, out of an average annual rainfall of 26 inches over the entire Thames Basin, only 13 per cent., or 3·4 inches of rain, is available for percolation.'

For percolation it is evident that storage for wells in

¹ *Nature*, December 12, 1907, p. 131.

the strata is meant, as the run-off must include the water that has percolated and been thrown out by springs. As the author remarks, with so small an average percolation, the pumping within the area 'may so closely approximate to, or even exceed, the percolation as to preclude any possibility of the recuperation of the subsurface supplies, 'especially during a period of long-continued drought.' The estimate agrees with that given by Sir John Evans for Chalk areas. (See p. 43.)

Attention was called in 1903 to the 'Shrinkage of the Thames and Lea' in a Report to the London County Council by Mr. M. Fitzmaurice. It was remarked that during the previous twenty years there had been an average decline over the Thames Basin of nearly $2\frac{1}{2}$ inches below the mean annual rainfall of $28\frac{1}{2}$ inches, as computed by G. J. Symons for forty years, 1850-1889. The conclusions were criticized by Dr. H. R. Mill, who pointed out that, 'on the whole, the rainfall was increasing slightly for fifteen years, and fell sharply in the last five.' He further remarked that 'the report shows plainly that the diminution in the flow of the Thames (and the same holds good of the Lea) is greater than the diminution of the rainfall. Theoretical considerations suggest that this is what should occur, for the amount of water absorbed by vegetation must be approximately constant, and in a dry year evaporation is usually more active than in a wet one, while, when the water-level in the pervious rocks is lowered, the flow of springs cannot respond to the rainfall with the promptitude usual when the rocks are saturated.'¹

As before indicated, the Metropolitan Water Board

¹ *Nature*, June 4, 1903, p. 105.

have deemed it 'desirable to seek Parliamentary powers enabling them to provide additional supplies from the Thames for as long a period as is economically practicable.'

In 1895 the Water Committee of the London County Council propounded a scheme for supplying water from a series of reservoirs constructed in the drainage areas of the Wye, Usk, and Towy, in the counties of Radnor, Brecknock, Carmarthen, Cardigan, and Montgomery; and it was reckoned that 415 million gallons a day could be obtained. The scheme was one which could be carried out by instalments. The principal reservoir would be on the site of the existing Llangorse Lake, in the Usk Valley above Brecknock. Aqueducts would convey the water to service reservoirs at Borehamwood on the north, and Banstead on the south, of London.¹

Perhaps the main objections to reliance on long-distance supplies consist in the possibility of the destruction of works during a time of warfare, or the dislocation of pipes by earthquakes. New York is, however, to be supplied with water from the Catskill Mountains by means of large reservoirs and an aqueduct ninety-two miles in length.

Among other British towns and cities which take their supplies mainly from rivers are the following:

Aberdeen.—From the Dee, about twenty-one miles above the city.

Barnstaple.—From the North Yeo stream.

Carlisle.—From the Eden.

Cheltenham.—In part from the Severn at Tewkesbury;

¹ Particulars and illustrations were given in the *Daily Graphic* for October 11, 1895.

in part from wells and from springs and reservoirs in the Cotteswold Hills.

Chester.—From the Dee.

Darlington.—From the Tees.

Doncaster.—From the Don.

Durham.—From the Wear.

Ely.—From the Great Ouse.

Hereford.—From the Wye.

Knarborough.—From the Nidd.

Leamington.—From the Leam.

Leeds.—From the Wharfe and Washburn.

Limerick.—From the Doonass Rapids in the Shannon, about seven miles above the city.

Newark.—From the Trent.

Norwich.—From the Wensum.

Oxford.—From the Isis or Upper Thames at King's Weir, north-north-west of Godstow.

Reading.—From the Kennet.

Ripon.—From the Ure.

Shrewsbury.—From the Severn.

Stockton and Middlesbrough.—From the Tees.

Worcester.—From the Severn.

York.—From the Ouse.

Some other towns take supplies from Valley Gravels, which are fed mainly by the rivers. (See p. 148.)

PONDS, DEW-PONDS, AND LAKES.

In Foulness, or Fowlness, the only means of water-supply at one time were ponds or tanks for rain-water. Supplies are now obtained by artesian wells carried into the Lower Eocene sands above the Chalk.¹

In some clay-districts in the Midland and South-

¹ W. H. Dalton, *Essex Nat.*, xv., 1908, p. 118.

western counties, ponds, and even ditches as well as brooks, are at the present day the only sources of supply to some isolated cottages. They are naturally liable to pollution, and in winter weather to be frozen.

In old times on the Weald Clay of Kent, where water could not be obtained from wells, there were ponds called Servers, to supply water to cottages, the name being used to distinguish them from horse-ponds.¹ On some upland regions where spring-water can be conveyed by gravitation, ponds for cattle are replaced by iron tanks, whereby the supply is maintained in a comparatively pure condition.

Dew-ponds, to which allusion has previously been made, are shallow circular excavations on the Chalk downs, from about 4 to 6 feet deep, and from 30 to 40 feet, and occasionally as much as 70 feet, in diameter.

Their method of construction differs to some extent, but for the most part the base was lined with clay, above which was placed a layer of straw, and then a layer of stones or rubble. Water or snow is said to have been introduced at first in some instances.

The information on the subject has been summarized by Mr. E. A. Martin, who for some years has given special attention to it.

He has remarked that 'Every pond on a high situation is not necessarily a "dew-pond," and the ponds which are being built nowadays on the chalk hills are placed in such a situation, as I am informed by a practical pond-maker, that there should be some sort

¹ Rev. S. Pegge's 'Alphabet of Kenticisms,' 1736 (*English Dialect Soc.*, 1876).

of natural runnel to convey surface drainage into the pond.' Many of the modern ponds are cemented.

The peculiarity in dew-ponds is that they are placed in elevated situations, and are excavated in a porous formation far above the plane of saturation—it may be 100 to 400 feet. Hence the supply of water can come only from the direct rainfall, snow, mist, dew, and the surface soakage from the soil and Chalk around the margin of the pond.

Dew-ponds occur on the Chalk downs, mainly, of Wiltshire, Hampshire and the Isle of Wight, Berkshire, and Sussex; and they have not been observed on the northern side of the Thames Valley in Hertfordshire, in Midland counties, nor farther north, nor in Ireland. Dr. H. R. Mill, however, has compared with them some of the ponds that occur at high levels on the plateau gravel on the borders of Middlesex and Hertfordshire, as on Mill Hill and Totteridge.¹ Other ponds, not necessarily dew-ponds, occur on Chalk uplands where there are tracts of Clay-with-flints, which naturally support water.

In his 'Natural History of Wiltshire,'² written between 1656 and 1691, John Aubrey remarked: 'The downes of Wiltshire are covered with mists, when the vales are clear from them, and the sky serene;' and he called attention to certain ponds on the east side of the down of Broad Chalke, called the 'Mearn-pitts,' which have always water in them. They were evidently Dew-ponds.

Gilbert White, who appears to have given the earliest description of such ponds (in 1776), considered that

¹ *Geograph. Journ.*, August, 1909, p. 191.

² Edited by John Britton, 1847, p. 15.

they were fed by dew and fogs (mists). Mr. Martin is of opinion that the supply, independent of rainfall, etc., is mainly kept up by mists.¹ It has been considered that the amount of dew deposited in this country is about $1\frac{1}{2}$ inches per annum, and that twice that quantity of water has been received in a dew-pond without the aid of rain. Moreover, according to Mr. J. Aitken, the greater proportion of moisture deposited as dew is derived from the ground.

Chemical analyses show small quantities of sodium chloride in the water of some dew-ponds, and this may have been derived from rain or sea-mists.

Many dew-ponds have supplied water for cattle at times when it was scarce, or not to be had in the low-grounds. Indeed, Mr. F. J. Bennett has remarked that a thousand sheep have been daily watered from some of the ponds in seasons of drought.² Nevertheless, it is admitted by Mr. Martin, and by others, that some of the best ponds have occasionally dried up. That the ponds are made in situations where the rainfall is greater and the evaporation less than in lower grounds cannot be questioned. Mr. George Hubbard has remarked that the average rainfall on the tops of the South Downs is 35 to 40 inches, and the annual evaporation not more than 20 inches.

In some cases in the Ligurian Alps, after a season of exceptional drought and small winter snowfall, it has been observed that springs on the lower slopes of hills had ceased to flow, while those on higher grounds were maintained by moisture from sea-winds.³

¹ *Trans. S.E. Union of Scientific Societies*, 1908; *Geograph. Journ.*, 1909, p. 174; see also L. C. Miall, *Rep. Brit. Assoc.* for 1900.

² *Proc. Geol. Assoc.*, x., 1888, p. 377.

³ W. Parkinson, *Knowledge and Sci. News*, October, 1907, p. 225.

LAKES.

In West and South Norfolk, at Wretham and Scoulton, also at Diss, there are a certain number of Meres, which occupy basins in the Chalk, due probably to dissolution of the limestone; they fluctuate in level according to the plane of saturation.

Other Meres in the Fenland, as at Whittlesea, Ramsey, and Ugg, have been drained.

Meres also occur in Cheshire, some due to subsidence of the ground, caused by the removal of rock-salt; while others, as noted by Dr. A. Strahan, occupy hollows in the Glacial Drift of Delamere Forest.

Lakes serve as natural reservoirs for rivers, tending to prevent floods; but in all cases they receive a certain amount of sediment, according to the nature of the bordering rocks, notably in the shallow Broads of East Anglia. While they receive much rainfall, they increase the amount of evaporation in dry weather, and thus diminish the run-off to sea. The evaporation from reservoirs and lakes has been estimated to be not more than 20 inches per annum in Britain, but may amount to $\frac{1}{10}$ inch in a day.

It is chiefly the more or less rock-bound lakes that have been utilized in Great Britain as sources of water-supply to large cities, as they occur at levels where the water can be supplied by gravitation.

The capacity has sometimes to be increased by raising the barrier, and it is important to ascertain whether this is formed of solid rock or of Glacial Drift.

The principal lakes of which advantage has been taken for water-supplies are Loch Katrine in Perth-

shire, utilized for the supply of Glasgow,¹ and Thirlmere in Cumberland, for Manchester. In Loch Katrine the water-level was raised 4 feet. The area is about 3,000 acres, and the increase of 1 foot in depth was calculated to impound more than 800 million gallons, as stated by Mansergh. Aberystwith is supplied from Lake Rheidol, near Plinlimmon, Colwyn Bay from Lake Cwlyd, near Trefriw, and Llandudno from two lakes west of the River Conway.

Oban is supplied from Loch-na-Gleann-na Bhearach, about four miles to the south of the town, the capacity of the lake having been increased by a dam.

Whitehaven is supplied from Ennerdale Water, and Workington from Crummock Water.

IMPOUNDING RESERVOIRS.

Reservoirs are constructed by means of embankments across the mouths of mountain or upland valleys, so as to impound the waters of the springs and streams, together with the direct rainfall. In quality the water is usually soft, and sometimes peaty.

The quantity to be expected depends on the rainfall, the acreage of the gathering ground, and the nature of the strata; while the storage capacity depends on the extent and depth of the area to be enclosed. Evaporation, loss by percolation, and the effects of frost, have of course to be considered.

A favourable site may be found in a valley excavated in porous strata of sandstone alternating with im-

¹ For particulars relating to Scottish lakes, see the 'Bathymetrical Survey of the Fresh-Water Lochs of Scotland,' by Sir John Murray and F. P. Pullar (*Geograph. Journ.*, 1900, and later years).

pervious beds that dip inwards into the hill-range away from the site of the dam. It is desirable that there be a thick, impervious base of clay or shale, occupying a fairly broad area between the hillsides. Where the valley becomes narrower, and is bounded by strong shoulders of rock based on clay, a site just above the narrower part affords the best foundation for the embankment. Thus, an area having a gentle slope, and partially hemmed in by steep banks, affords a promising site, and water may be impounded to depths varying from about 30 to 150 feet.

So long as a good impervious formation underlies the site, the presence of a flooring of valley gravel is rather an advantage than otherwise.

Sites that are by no means ideal have sometimes to be utilized by the skill of the Engineer.

As remarked by Sir A. R. Binnie (1887), where the rocks are bent into an anticline, and where the dip of the strata is from the higher towards the lower part of the valley, the positions for reservoirs are not good. A synclinal structure may be advantageous, and the drainage area should be open to the prevalent rain-bearing winds.

Excellent sites may be found in valleys that occur among dense, impervious slaty rocks with grassy slopes, and in such situations it has been estimated that the available rainfall may be 60 per cent. or more of the mean annual amount, received directly or through springs.

The amount would be considerably less where the strata are very pervious, and their inclination tends to conduct the underground water away from the valley, and as a rule about $\frac{2}{5}$ of the mean annual rainfall is all that is relied upon.

In the areas of Carboniferous Rocks, such as the Millstone Grit and Yoredale Rocks, faults and joints may prove troublesome among the hard bands that alternate with shales. In regions where Coal or Rock-salt is worked, danger and trouble may arise from subsidences and loss of water.

Where the rain sinks into porous and jointed strata down to a bed of clay, joints are enlarged into fissures by dissolution and mechanical erosion, and loose sandy material may be carried away by springs, leading to slight disruptions of the overlying strata.

Such subterranean erosion leads to landslips on rocky coasts and inland scarps, especially where there is a slight inclination in the strata towards sea or valley.

It is of great importance, therefore, to ascertain whether the bordering rocks of a reservoir site, and especially the banks or abutments which support the dam, are free from any tendency to land-slides. The bursting of a reservoir near Bradfield, for the supply of Sheffield, took place in 1864, and was attributed to the effects of a landslip on the eastern side of the embankment that extended under a portion of the outer slope.

Mr. C. Hawksley (1904) remarked on the possible injury that might be caused to an earthen dam by a water-spout, but knew of no case where this had occurred.

In large impounding reservoirs, the hedgerows, trees, accumulations of peat, and any specially contaminated soil, are cleared away.

It is desirable that the collecting ground or catchment area should be as free as possible from peat-bogs, not always possible in moorland regions, and that

it should consist of uncultivated tracts. Grass, and especially woodland, should replace arable land, so that there be no source of contamination from manure.

The character of the vegetation, as well as that of the strata and the steepness of the slopes, naturally influence the rate of flow off the surface; and the amount of mud or silt carried down has to be taken into consideration.

An intimate knowledge of the geological structure is needful, so as to determine the dip and succession of the strata, the presence of any faults or other disturbances, and of the occurrence of Boulder drift. In most cases, especially in reference to sites for dams, trial-holes are necessary.

Reservoirs for water-supply to towns have been made in the Silurian and older rocks of Wales, in the granite districts of Cornwall, in the Devonian slaty rocks, in the Carboniferous rocks of the Midland and Northern counties of England and South Wales.

Reservoirs for canals have been made in the Lias clays, in the London Clay, and other impervious strata. Ornamental lakes have been constructed in the marls and limestones of the Great Oolite, as at Blenheim Park; and in many situations on clay, or where porous strata are based on clay.

In the Great Oolite of Oxfordshire, in the valleys of the Glyme and Dorne, there is a considerable proportion of clayey matter, marl and argillaceous limestone alternating, and the slopes of some of the valleys are coated with rubbly clay. In tracts of massive limestone, undivided by bands of shale or clay, no good sites for reservoirs are to be expected; but excavations made in porous strata on low ground bordering a river

have been suggested. (See p. 124.) In such situations large storage reservoirs are sometimes constructed, in part by excavation, and in part by embankments, as at Staines.

Additional water, as noted by Mr. Charles Hawksley (1904), is sometimes obtained on reservoir sites by catch-waters or conduits along the higher slopes of the valley below the dam, but at sufficient elevation to conduct the spring-waters into the reservoir.

Among other engineering questions to be considered are the nature of the embankment, whether of earth or masonry, of the outlet works, the character of the waste-weir or spill-way for surplus and flood-waters, and of the by-wash channel to exclude any undesirable stream. Dams are usually constructed about 5 feet above the top water-level.

The puddle-wall and wing-trenches, where needful, are carried down to a good foundation of impervious clay or solid rock below the outlet of any springs likely to prove dangerous. Beneath the valley the trench may be from 60 to 80 feet deep, and sometimes a good deal more, with corresponding increase in the hillsides. Masonry dams especially require a good solid foundation of rock.

Gravelly clay is sometimes recommended for puddling, and the use of sandy clay may be advantageous for positions near the surface, where stiffer clay would be liable to become fissured in dry weather.¹ Concrete is also used.

Mansergh mentioned that in the construction of the Woodhead reservoir, the highest of the series in the

¹ On varieties of clay suitable for puddle, see W. Gallon, *Proc. Inst. Civ. Eng.*, xciv., 1888, p. 231.

Longdendale Valley for the old supply of Manchester, the trench for the puddle-wall had to be excavated 167 feet below the surface of the ground, owing to the disturbed nature of the strata. In the Yeo reservoir for Bristol the puddle-trench was carried to a depth of 175 feet.

Slight leakage into porous strata bounding a reservoir may not be harmful; in the case of the Brent reservoir at Hendon, there is a slight leakage at times near the dam on the northern margin, through gravel which overlies the London Clay.

Of excavated and covered service reservoirs, the largest in the world is the Beachcroft reservoir at Honor Oak, constructed by the Metropolitan Water Board. It holds sixty million gallons of water, equal to one day's supply for a quarter of the population served by the Board.¹ The water is conveyed from Hampton, and filtered as it enters the reservoir.

It is necessary that service reservoirs be covered, as the exclusion of light prevents the growth of aquatic plants, such as algæ.

Service reservoirs are usually constructed so as to yield a supply for not less than twenty-four hours, preferably for one week, or even longer; whereas storage reservoirs in this country should contain supplies requisite to last from 100 to 200 days. Indeed, Sir A. R. Binnie (1887) would allow from 160 to 300 days' supply in the east and south-east of England, in accordance with the estimated rainfall; while in parts of India the storage of a two years' supply may be necessary.

Subsiding reservoirs or settling tanks are required

¹ *Ill. Lond. News*, May 25, 1909.

sometimes at the head of storage reservoirs to receive the silt of flood-waters.

Compensation, reckoned at $\frac{1}{3}$ the average flow of a stream, has to be made to those who have rights below the intake—such as riparian owners, farmers, mill-owners, fish-associations, etc. This right may extend for twenty miles below the intake, but not into navigable waters.

Separate compensation reservoirs are sometimes constructed to retain storm and flood water so that it can be used in dry seasons.

Filtration of reservoir water may or may not be required, but it is recommended by Mr. C. Hawksley (1904) for waters from all gathering grounds, as it removes not only matters in suspension, but the discoloration due to peat.

Professor S. J. Hickson has remarked on the unpleasant smell in the water of a certain reservoir, caused by the presence of the fresh-water snails, *Limnæa peregra*. He also drew attention to the fact that the mains supplying Manchester had become choked with fresh-water Polyzoa which resembled 'moss,' and about 700 tons had to be removed by an expensive process.¹

The following cities and towns are chiefly supplied by impounding reservoirs:

Belfast.—From reservoirs in the Basalt district at Stonyford, west-south-west, and Woodburn, north of Belfast; also from the Kilkeel Valley, in the granite of the Mourne Mountains about 40 miles south of Belfast.

Birmingham.—Main supply from reservoir in the Elan

¹ Address, Zoological Section, *Brit. Assoc.*, 1903.

Valley, fed by tributaries of the Wye, at Cwm Elan, Nantgwyllt, near Rhayader in Radnorshire.

Bradford.—From reservoirs in the valleys of the Wharfe, north-east of Skipton, the Aire and tributaries, on Millstone Grit and Yoredale Rocks.

Bristol.—In part from pumping-station at Chelvey, etc., and from the Yeo reservoir, on the northern borders of the Mendip Hills.

Cardiff.—From area of about 4,000 acres in the Old Red Sandstone of the Brecknock Beacons.

Dublin.—From reservoir fed by River Vartry, near Roundwood, Co. Wicklow.

Edinburgh.—Springs from Pentland Hills, and reservoirs impounding water on the Moorfoot Hills. 'The capacity of the reservoirs is fixed as equal to six months' yield of the district draining into them, which experience has proved to be sufficient for equalizing the yield of three dry years consecutively.' This statement was made by the engineers in 1892, when the waterworks were calculated to yield about 15 million gallons per day to a population of 371,000, and with a daily consumption of about 40 gallons per head, including what was required for trade and sanitary purposes (Brit. Assoc. Excursion Handbook, Edinburgh Meeting, 1892, p. 101). In 1907, with a population of 435,500, about 17 million gallons per day was delivered.

Leicester.—Mainly from reservoirs in the district of Charnwood Forest, capable of storing more than 1,300 million gallons of water. In September, 1909, there was a deficiency in the reservoirs, amounting to about 1,000 million gallons, owing to drought. The maximum day's supply for the area supplied is, however, about $6\frac{1}{4}$ million gallons. The water is soft.

Liverpool.—Main supply from reservoir (Lake Vyrnwy) in north-west Montgomeryshire, east of Aran Mowddwy, near head of River Vyrnwy, a tributary of the Severn. Site on

Ordovician rocks. Length, $4\frac{3}{4}$ miles; average width, $\frac{1}{2}$ mile; greatest depth, 84 feet; area, 1,121 acres. The dam is 1,172 feet in length. The reservoir is calculated to hold more than 12,000 million gallons. The mean annual rainfall is 65 inches, and the drainage area above the dam is about 18,000 acres. Distance, 67 miles from Liverpool. The total area of the gathering ground, now all the works have been completed (in March, 1910), is 22,742 acres.

Prior to 1892 the city was supplied in part from deep wells in the New Red Sandstone, and in part from reservoirs on the moors at Rivington, north-east of Wigan, and about 24 miles distant from the city.

Londonderry.—Supply mainly from reservoirs on the Creggan Burn, west of the town, and in part from reservoirs on the eastern side.

Manchester.—In part supplied by five reservoirs in Longdendale Valley, about 18 miles east of city; fed also by springs derived from the Millstone Grit, etc., and specially conducted into reservoirs. The works, according to Mansergh, were calculated to supply 38 million gallons daily, from which about $\frac{1}{3}$ had to be deducted as compensation water. The watershed area was nearly 20,000 acres, and the rainfall about 50 inches.

Manchester has since 1894 been in part supplied from Thirlmere by means of an aqueduct nearly 96 miles long, and constructed to carry 50 million gallons of water daily.

Newcastle.—Largely from reservoirs at Whittle Burn, Hallington, Little Swinburn, and Colt Crag.

Plymouth.—From reservoir formed by Burrator Dam, on the River Meavy, near Sheepstor, in the granite area of western Dartmoor. The gathering ground is reckoned to be more than 8 square miles, while the reservoir or lake occupies $116\frac{1}{2}$ acres, and is 77 feet in the deepest part.

Sheffield.—Reservoirs on Millstone Grit moorlands to

west and north-west, at Redmires near Stanedge, Bradfield, Strines, Dale Dike, Damflask, and Langsett.

Swansea.—From reservoirs calculated to hold more than 15,000 million gallons, and fed by the water from the Crai Valley, the Lliw, and Blaen-nant Ddu streams.

Malvern, Penmaenmawr, Rhyl, Prestatyn, and other towns, are supplied by reservoirs impounding springs and upland or mountain streams.

CHAPTER VIII

UNDERGROUND SOURCES OF WATER-SUPPLY

THE term **Well** is often applied to an opening in the ground, whether natural or artificial, where water can be obtained.

If a spring be impounded in a shallow excavation or trough by the roadside, the term **Dip-well** is applied.

A shallow well, when dug to a depth not exceeding about 30 feet, may be worked by ordinary pump. Wells dug to that or a much farther depth, when used for a cottage or small house, are worked by bucket and windlass, and termed **Draw-wells**. In some cases they are 160 feet deep, and the labour in raising a heavy bucket of water is great.

Technically the term **Well** is sometimes restricted to a shaft, a dug or sunk **Well**, as distinct from **Borings** which are driven or drilled ; but the distinction is not maintained, as the terms **Well-sinking** and **Well-boring** are both in common use. Moreover, so-called 'horizontal wells,' or **adits**, are sometimes driven into the sides of hills to open up springs concealed by talus or landslips, or to tap the water-bearing strata farther below ground in a hillside.

Tunnels, **galleries**, or **headings** of similar nature, are also driven from the base, or near the base, of a sunk-

well to increase the supply of water from the porous strata. They may be excavated along the strike of the strata, or in an oblique direction towards the outcrop, if the dip of the strata favours a further supply. They are sometimes 4 feet wide and 6 feet high. Dumbwells have also been made for diverting surface-waters underground. (See p. 77.)

Surface, Percolation, or Infiltration Wells, in the form of pits or trenches, have sometimes been constructed on the borders of river valleys where there is a broad tract of gravel, and the water percolating from the river undergoes a certain amount of natural filtration. Such sources are, however, liable to be affected by flood-waters.

A large ballast-pit near the Thames at Oxford has been used for supplementing the water-supply to the city, the base of the pit having been carried below the ordinary level of the river-water.

Water is sometimes taken from culverts or arched drainage-channels excavated in gravel beds. (See p. 148.)

In some tropical regions where the rainfall is uncertain, the evaporation great, and the streams flow at the surface only during the time of heavy rains, large percolation wells have been sunk through thick Alluvial deposits, which when they comprise alternations of sand and clay may yield flowing wells, as in Baluchistan.

Stored water under pressure may be found in estuarine and marine deposits bordering the sea-coast, and fed by drainage from mountain lands. Such water is sometimes brackish, as was the case in a boring 150 feet deep in the Federated Malay States, as noted by Mr. J. B. Scrivenor.

Excavations in the form of trenches and tunnels, or underflow canals cut below the plane of saturation, have been suggested by Mr. Whitaker in reference to the Chalk where it bounds a river-course.

'Water is obtained from the sandy dunes along the coast of the North Sea at the Hague by laying covered porous drains to the pump wells; the suction pipes are laid in a column of sea-shells to prevent the holes being blocked by the sand. From 30 to 50 per cent. of the rainfall can be collected in this way,' as noted by Mr. S. C. Bailey.¹ On higher grounds where gravel and sand rest on an impervious foundation, elongated surface wells trenched beneath the water-bearing strata have been suggested, according to Slichter (1902).

No hard-and-fast line is to be drawn between **Shallow and Deep Wells** so far as actual depth is concerned, when supplies are derived from direct rainfall. Both shallow and deep wells may draw supplies from porous strata of fairly uniform character, such as Chalk and New Red Sandstone, that may extend downwards from the surface without impervious covering or parting. Shallow wells may derive water within a depth of 30 or 40 feet from strata that are intercalated between impervious clays, and they may sometimes be of an artesian character.

Deep wells may be regarded as those 100 to 350 feet or more in depth. In China wells have been sunk as deep as 1,500 feet.

Ordinary shallow surface-wells deriving supplies within 40 feet below-ground from porous strata, such as sand and gravel, or sandstone, that are exposed at the surface, may be liable to contamination from

¹ *Engineer*, April 6, 1906, p. 335.

soakage of polluted water through the soil and subsoil. It is therefore desirable that the mouths of wells be protected in all cases by a cemented ring 1 foot or more above the surface, to keep out surface drainage; and that the wells be lined with cemented brickwork or other material some depth below the surface, to prevent impure soil and subsoil water from entering.

Some shallow wells in Alluvial grounds or clay-vales derive supplies simply from the surface-soaking of water through porous soil. They are used by cottagers where no other supplies from wells are available. For drinking purposes rain-water is preferable.

The yield from shallow wells is much more limited than that from deep (non-artesian) wells, which draw from a larger gathering ground, although both are affected by the amount of direct rainfall. Shallow wells are thus especially liable to drought. Moreover, from the remarks already made, it is evident that such wells in porous surface strata are to be avoided in populated areas where the sanitary arrangements may be imperfect; they are more liable than deep wells to be affected by defective sewers, gas-pipes, etc., but the water, if contaminated, may be used for horticultural and stable purposes. In many sparsely populated areas there are shallow wells where the quality of the water is all that could be desired.

Wells are constructed up to 5 feet or more in diameter, and are usually lined or steined with cemented brickwork or stone, with concrete or cast-iron cylinders. Sometimes glazed stoneware pipes are used to keep out surface drainage. The depth to which the lining is carried will vary according to the nature of the strata and other circumstances. At lower levels it is often

necessary to line a shaft, when the strata are soft, or when springs of impure water, encountered above the main water-bearing strata, require to be tubbed out.

As a rule it is useful to sink below the water-bearing strata a few feet into the underlying impervious stratum, to afford a sump or small underground reservoir.

Shallow water-supplies are sometimes obtained by means of wrought-iron tubes driven into the ground through loose and soft strata to depths of from 20 to 40 feet. These are known as *Abyssinian tube-wells*, and they may supply 3,000 or 4,000 gallons of water a day, and in some situations as much as 1,000 gallons an hour has been obtained.

Where pumping by windmill is adopted, a reservoir is necessary to retain a sufficient supply for the times when wind fails.

Artesian Wells and Borings, to which some reference has already been made, are characterized by the uprising of the water when tapped by a shaft or boring. In some cases the water rises several or many feet above the surface of the ground, and in this case we have 'flowing' or 'spouting' wells. Flowing and non-flowing artesian wells occur in the same tract, dependent on the configuration of the ground. (See Fig. 131.)

The explanation is that the water is confined in a porous formation between inclined impervious strata, and the formation is charged with water near its outcrop at a higher level than it is in deeper portions. Thus, the supply which is tapped at a depth below the upper impervious stratum is forced upwards into the well or

bore-hole by the pressure of the head of water in the exposed porous rocks, and it rises to about the level of the plane of saturation in them.

The geological structure may be comparatively simple, as in certain wedgelike masses of sand and gravel, or of sandstone, that are sometimes met with in Drift or in Carboniferous and other rocks, which have an irregular or definite inclination from the surface. Here the supply, obtained from what is termed an 'artesian wedge,' is limited.

Flowing wells have been met with in the Drift of Norfolk near Wymondham and Attleborough, where water was tapped at depths of 55 and 60 feet.

In Fig. 28, A represents Boulder Clay; B, an irregular



FIG. 28.—ARTESIAN WATER FROM DRIFT.

wedge of sand yielding water which, if tapped below D, might rise to the surface; C is portion of a mass of sand resting on the Boulder Clay, and this would yield shallow surface supplies of water.

There are other structures that may cause an uprising of water along what has been termed an artesian slope by Mr. I. C. Russell (1902). The water in this case passes from the higher outcrop of the pervious bed 2 in Fig. 29 to a distant exit, marked by a cross, in a deep valley. If tapped along its course (beneath A, a bed of impervious rock), the underground water may rise to some extent if the friction sufficiently retards the flow.

It has also been suggested that the uprising of water

may, in certain cases, be due to the pressure of overlying deposits, when they attain a great thickness. Gas

pressure has likewise been cited as causing an outflow of water.¹ (See also p. 88.)

Other flowing wells, such as arise from a great depth and at a high temperature, are mentioned under Thermal springs (p. 302). They are deep-seated, but not necessarily artesian waters. Artesian waters are seldom yielded by crystalline rocks, but flowing wells may issue along planes of faulting and fracture, adjacent to them. (See Fig. 25, p. 86.)

The non-flowing wells are occasionally referred to as Subartesian or Artesioid, but these terms are not necessary.

Artesian supplies are sometimes obtained from inclined strata that rest against mountain tracts. Even Alluvial beds banked up and filling wide valleys in the form of fans, below mountain gorges, and extending on to maritime plains, may yield artesian supplies if they comprise alternations of porous and impervious strata with a seaward inclination. (See p. 123.) The structure is represented in diagrammatic form in Figs. 30 and 31.² A consists of a foundation of hard impervious rocks; B comprises clays with intercalated sands and gravels, and these

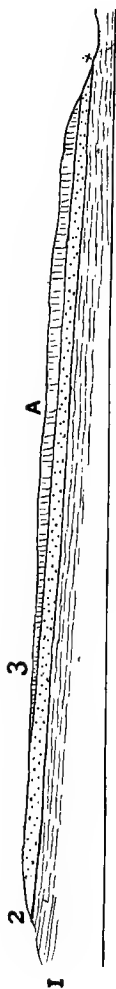


FIG. 29.—ARTESIAN SLOPE.

¹ R. Hay, *American Geologist*, v., p. 296.

² Based on section by H. Hill, *Trans. N. Zealand Inst.*, xli., 1909, p. 434.

pervious beds would yield water rising to the level of saturation at or near their outcrops.

Prestwich has noted that from sedimentary strata below the volcanic accumulations at Naples water was found at a depth of 1,524 feet, and rose to the surface with a discharge of 440 gallons per minute.¹

At Cleethorpes a boring in the bed of the Humber 400 yards distant from high-water mark reached Chalk at a depth of 72 feet, was carried in that formation to a further depth of 21 feet, and yielded 100 gallons a minute, a jet of water rising 16 feet above the foreshore. In Holderness generally, water which rises to the surface is met with in the lower grounds beneath 70 or 80 feet of Drift, and within about 20 feet of the top of the Chalk.² (See pp. 89, 93.)

Fresh-water is met with sometimes at considerable depths beneath the sea. Thus, at the Spithead Forts, off the Isle of Wight, water has been obtained from borings carried to a depth

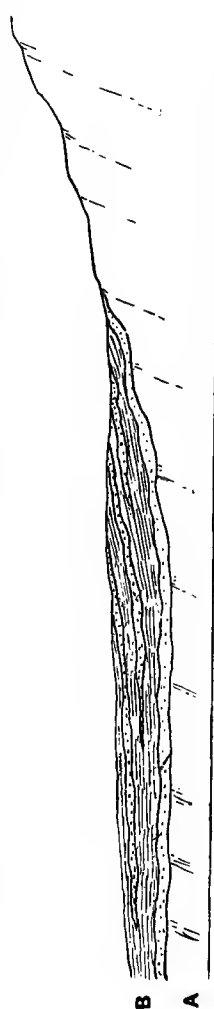


FIG. 30.—ARTESIAN WELLS ON COASTAL PLAIN: LONGITUDINAL SECTION.

¹ *Proc. Roy. Soc.*, 1885, p. 257.

² C. Reid, 'Geol. Holderness,' *Mem. Geol. Survey*, 1885, pp. 129, 136.

of about 570 feet through recent deposits and Bracklesham Beds, and it rises above Ordnance Datum.

At Bourne in Lincolnshire and in other parts of the county abundant supplies of artesian water have been obtained from the Lincolnshire Limestone, which has

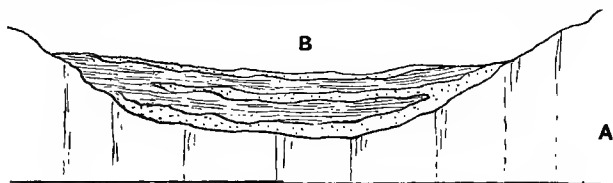


FIG. 31.—ARTESIAN WELLS ON COASTAL PLAIN :
TRANSVERSE SECTION.

a broad outcrop free from coverings of Drift. The supply is no doubt obtained from an artesian wedge, on a large scale, as there is no evidence of a basin. (See p. 81.)

In East Yorkshire a good supply has been obtained from the Corallian rocks, 4 in Fig. 32, which are faulted

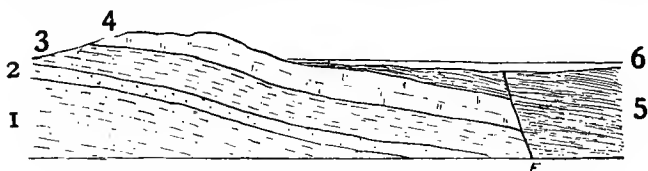


FIG. 32.—ARTESIAN WATER FROM FAULTED STRATA IN
VALE OF PICKERING.

against the Kimmeridge Clay, F. The water is there dammed up against the faulted Clay, and at the same time pent up between masses of Kimmeridge Clay above, and Oxford Clay, 3, below.

The underlying strata are 2, Kellaways Beds, and

1, Estuarine Series. The diagram is based on a section by Strangways.¹

In what is sometimes regarded as the typical structure of the ground yielding artesian water, the strata are bent into a syncline or basin, so that the waters pent up beneath the surface are fed by outcrops of porous strata on more than one side, as in Fig. 34.

Artesian basins are mostly irregular, and often faulted. In the diagram (Fig. 33) such structures are shown. At B a flowing well would be encountered, water being pent up in the sandstone between clays; at C the water would not rise to the surface, as the ground is slightly above the level of saturation in the bordering porous strata. At A possibly no water would be met with, as the pervious strata of sandstone are faulted away from any connection with the surface, and water could only get access along fault-planes, F. Water, under no artesian pressure, would be obtained from the sandstone at D and E.

Differences in the water-level

¹ 'Jurassic Rocks of Britain,' *Mem. Geol. Survey*, i., 1892, p. 488.

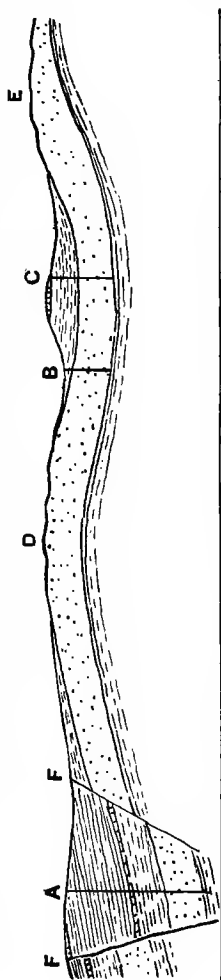


FIG. 33.—ORDINARY AND FAULTED ARTESIAN BASINS.

in wells in an artesian basin, while due in some cases to the interference by other pumping-works, may be caused by hard impervious layers of impersistent character,

such as tabular layers of flint in the Chalk, by faults and flexures, by dykes or sills of igneous rock.

In the more important artesian wells in this country, the structure, as in the London area, is that of a trough or shallow basin, so that the head of water extends through a considerable tract of country where the Chalk—the formation which receives most of the rainfall—rises north, west and south of London. The general inclination of the water-table on the northern side of the London Basin is estimated by Mr. J. Hopkinson (1891) at 24 feet to the mile in the higher Chalk tracts, and 12 feet to the mile in lower grounds. To the east of London, where the Chalk descends below the sea, the water is to a certain extent impounded by the ocean.

Fig. 34 is a diagram on a very exaggerated scale, to show the structure of the London Basin. A represents the Gault Clay; B, the Upper Greensand of the North Downs (not developed on the northern side of the basin); C, the Chalk; D, the London Clay and underlying Eocene strata; and E, the Bagshot Sands. In a



FIG. 34.—THE LONDON BASIN.

boring at E, water from the Chalk would naturally rise to about the level of the plane of saturation in the Chalk, marked by broken lines. At F water should rise to the surface and overflow.

When deep wells and borings were first made in the London area, the water obtained beneath the lower grounds rose above the surface—from 5 to 10 feet between Wandsworth and Mitcham, and 1 to 3 feet near Waltham Abbey, Edmonton, and Tottenham, as recorded by Prestwich (1851); but at that date, although some of the flowing wells still continued, a gradual depression of the plane of saturation, or depletion of the water, beneath London had taken place. Many of the earlier wells derived their water from the Lower Eocene Sands (Thanet Sands or Woolwich and Reading Beds), the water in which was not separable from that of the Chalk. Large quantities were obtained, but the yield would not be so free as that from a good fissure in the Chalk.

In time many wells had to be deepened; that at Combe's Brewery, as noted by Beardmore (1862), was lowered 60 feet and more in the course of twenty-five years. Mr. J. Hopkinson (1891) mentions a well in which the water in 1821 or 1822 stood at $12\frac{1}{2}$ feet above Ordnance Datum. In 1881 it was 105 feet below O. D., a lowering of 117 feet in sixty years. The yield in many cases has likewise diminished.

The level of the water in areas outside London in 1851 had not then fallen so much, but the decrease below London, though variable, had been on the average about 2 feet per annum during the thirty years, 1821-1851; and at the last-mentioned date the

quantity pumped from beneath London was estimated at from 10 to 12 million gallons daily.

At the present day the water-level in the Chalk below the City of London is said to be about 100 feet below Ordnance Datum, and to vary from 130 to 140 feet below the surface, while the annual amount of depression is from 1 foot to 2 feet. This depression is experienced as far as Ilford, as noted by Dr. Thresh (1901), where the fall in thirty years has been 63 feet.

In Chicago, as noted by Slichter (1902), there has been a depression of the water-level of about 100 feet in forty years, and at Denver many wells have failed by the over-pumping.

Below London the underground level of saturation in the Chalk has thus been gradually lowered since artesian wells and borings were first made, but the lowering is by no means uniform. Occasionally a flowing well may be encountered near the margin of the basin, as at West Drayton, and elsewhere undulations and faults bring the Chalk somewhat nearer the surface.

The yield recorded from particular wells, when used as a guide for prospective supplies, must be taken with respect to the dates when the quantities were estimated.

At present supplies of from 1,500 to 8,000 gallons per hour, and occasionally 10,000 gallons or more, have been obtained from the Chalk in the County of London. At St. Albans in 1877 as much as 30,000 gallons per hour were obtained at a depth of 266 feet (236 feet in Chalk), and at Cheshunt 125,000 gallons per hour were obtained at a depth of about 576 feet (474 feet in Chalk).

Mr. Clayton Beadle (1908) has estimated that from

100 to 200 million gallons per day are drawn from the London Basin by private wells.

As the Chalk can only hold a certain amount of water, every portion taken from it artificially is so much lost to the springs and streams which are fed from the overflow. Thus, it is not surprising that the Ver and Colne and the Lea are declining, as pointed out by Mr. Hopkinson (1891). The Cray, again, as already mentioned, has likewise been affected.

It would thus appear that we are drawing upon capital or old storage, sometimes termed the 'water of cisternage.'

The effects of much pumping on adjacent springs and streams may be very serious. Some years ago it was proposed to draw large supplies of water from the Chalk at Heydon, and from other borings in the drainage area of the Cam, to supply parts of Essex. It was then contended that the withdrawal of so much water from wells meant an almost equivalent loss to the Cam drainage. In some artesian wells at Cambridge from which at one time the water rose above the surface, this is no longer the case.

Proposals have been made for the construction of charts, showing the levels to which artesian water will rise by means of lines of equal water-pressure or isopotential lines.¹ The force of the uprise of water is sometimes so great that earth and stones have been ejected. The pressure dependent on the head of water or static head in the more elevated portions of the water-bearing strata will, however, be subject to considerable fluctuations due to variations in rainfall and the amount abstracted by pumping.

¹ See Beadnell (1909)

Some attempts have been made to represent the underground water-contours in the Chalk and other strata in the south-east of England;¹ but probably a map of the underground contours of the Chalk itself would be of more permanent practical value, and an attempt in this direction has been made by Mr. W. H. Dalton.²

Cone of Exhaustion.—Where large quantities of water are required, both wells and borings must be carried, if possible, to a considerable depth below the permanent plane of saturation in porous strata that extend from the surface at the pumping-station.

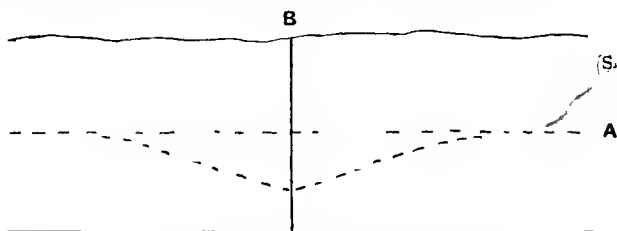


FIG. 35.—PLANE OF SATURATION OR REST-LEVEL, AND CONE OF DEPRESSION OR PUMPING-LEVEL.

This is necessary owing to the fact that pumping locally lowers the water-plane, producing what is known as a Cone of depletion, depression, or exhaustion. The water-level, depressed during pumping from well or bore-hole, only regains its normal position or Rest-level after the operations have ceased. The cone,

¹ See Lucas (1880): 'Water-Contours in the Chalk Gathering Ground of the River Wandle, by J. T. Harrison, *Proc. Inst. Civ. Eng.*, cv., 1891, p. 8; 'Sub-Surface Water-Contours in the Chalk of Hertfordshire, Dorset, and Hampshire,' by Baldwin-Wiseman (1907).

² See Thresh (1901), p. 17, map of the Sub-Tertiary Contour of the Chalk in Essex.

which is inverted, is shown diagrammatically in Fig. 35, B marking the site of a boring, the horizontal broken line the ordinary plane of saturation, and the curved portion the cone of exhaustion produced by pumping.

The size of the cone of depletion varies according to the nature of the strata and the amount of water withdrawn. According to Mr. Baldwin-Wiseman (1907), the sides of the cone are steeper in Chalk than in sandstone, and are probably curved, the shape varying with the frictional resistance of the strata. In ordinary cases the cone may extend from about 100 to 500 yards, and sometimes to half a mile in width.

This depression in the saturation-level occurs naturally on the borders of a valley where springs issue from permeable strata. (See Figs. 13, 20.)

The difference between the rest-level and the pumping-level may amount to as much as 100 feet in porous and fissured strata. The extent of the cone of depression is therefore important, not only in regard to its influence on adjacent wells, but in reference to the influx under certain conditions of contaminated water.

Interference of Wells.—Where the water-bearing strata are much jointed, the influence on other wells will extend farther than in the case of sands and other beds devoid of fissures. This 'interference' of one well with another may be felt for several miles. In the New Red Sandstone district of Liverpool the effect of pumping has been noted to affect wells nearly two miles distant.

R. F. Grantham has recorded that the effects of pumping 2 million gallons of water a day from two wells in the Chalk of Essex permanently lowered the

water-level as much as 14 feet in nine years, and affected the wells for a mile around.¹

Mr. F. H. King has given the results of pumping from two wells sunk in sandstone at a distance apart of 1,133 feet. When pumping from one well at the rate of about 75 gallons per minute, a fall of water was detected in the other well after the lapse of 1 minute and 45 seconds. The pump was worked for 10 minutes, and the fall of water in the second well continued for nearly 15 minutes.²

The depression in the standing water-level of the Chalk under London is an example on a very large scale of the lowering of what is termed the 'artesian pumping-level,' in strata from which immense quantities of water are drawn. This depression has become to a large extent permanent, and independent of any local cone of exhaustion due to the immediate effects of pumping at one well.

FAILURES OF SUPPLY.

In seasons of drought both shallow and deep wells may fail, and this is sometimes to be remedied by sinking or boring to a further depth. Sometimes water may be lost by deepening a well, if carried through an impervious layer into strata below that are not saturated. Such loss may be temporary or permanent, according to the geological structure.

Wells have a great advantage over borings, inasmuch as they afford a greater chance of traversing water-bearing fissures, and there is the opportunity of driving

¹ *Proc. Inst. Civ. Eng.*, cv., 1891, p. 71.

² Nineteenth Ann. Rep. U.S. Geol. Survey for 1897-98.

headings which may considerably increase the supply, and likewise act as reservoirs for pumping. In the Chalk especially it is desirable to sink below the permanent plan of saturation and drive headings. (See pp. 122, 126.)

The freezing of water in shallow wells and reservoirs has to be considered.

Both wells and borings, when carried into sands, are liable to be choked with quicksands, which pass through perforated tubes. By means, however, of an air-lift or sand-pump the running sands can be removed day by day or at intervals. Sometimes a metal sand-strainer is found sufficient to exclude the sand.

Intermittent flows from a bore-hole may be due to the temporary choking of the pipes by sand.

It may occasionally happen that the boring process, especially that known as 'jumping,' may clog or seal up cracks in water-bearing rocks, such as slightly argillaceous limestones. Pumping may after a time remove the coatings. According to Slichter (1902), a restoration in the flow of water has sometimes been produced by forcing large quantities of water down the bore-hole. At times, also, water may be lost through imperfections in the lining or tubing.

Where wells and borings have been carried to a considerable depth in strata that are naturally water-bearing, like the Chalk, and no fissure yielding a supply has been met with, dynamite has been employed as a last resort at the base of a well or boring to open up fissures, and sometimes with success. In a deep boring at Hampstead 16 pounds of dynamite were, however, used without any satisfactory result.¹

¹ Summary of Progress, *Geol. Survey* for 1906, 1907, p. 149.

In a shaft sunk at Fort Regent, Jersey, about the year 1806, a blast was fired at the depth of 234 feet, and water issued, probably from a fissure, rising 70 feet in the well, or about 6 feet above high-water mark.¹

In connection with borings, it has been usual to commence with a sunk well of 10 to 30 feet, or even more, in depth, convenient for the pumping machinery; but shafts are often carried to a much greater depth before boring is commenced. This plan is not always adopted; borings are sometimes commenced at the surface, and the water-tight steel tubes are ultimately raised above ground.

Borings from 3 inches to as much as 5½ feet in diameter are made, but it is not usual to have a boring of more than 2 feet in diameter, and the size is diminished with the depth.

In Texas borings (for oil) have been carried to a depth of more than 3,000 feet, in Queensland a boring has been made to a depth of 5,046 feet, and in Silesia one was made to a depth of 6,573 feet.²

It is hardly necessary to say that suitable drinking-water is not to be expected at such depths.

In soft strata boring may be performed by auger, which is turned and jumped, or by chisel-ended drill in the same manner. The jumping process reduces the harder bands of rock to powder or small fragments, and the material comes up in the form of sludge or slurry, which as a rule is of little help to the geologist in deciding the character and position of the strata.

¹ Ansted, 'Applications of Geology to the Arts and Manufactures,' 1865, p. 93.

² S. C. Bailey, *Engineer*, April 6, 1906, p. 335.

Drilling by means of a steel crown set with diamonds (the amorphous stones known as 'bort' and 'carbonado'), or with hard steel in the case of the 'calyx drill,' are processes most satisfactory from the geological point of view.

Records of the strata passed through in well-borings must be interpreted with caution by the geologist, when the particulars are given by the foreman of works. Thus, sandstone is sometimes applied to oolite, flint to septaria, and 'hard rock' may be an indurated band of marl or shale in a clay series.

In drawing up records of wells and borings, it is desirable to note as many of the following particulars as possible :

The precise locality, and county or district.

The height of the ground above Ordnance Datum.

Object of well or boring.

Whether dug well or boring, and their dimensions ; or if well only, whether headings have been made.

The date when completed.

The nature and thicknesses of the strata, and depths.

The depth at which water was reached.

The yield of water, the rest-level after pumping (with date), and any fluctuations noticeable at different seasons.

The temperature and quality of the water, with analysis.

The names of the well-sinker or borer, and of the analyst.

Records of strata have sometimes been drawn up by a Scottish workman accustomed to sinking coal-shafts ; and in consequence local mining terms, such as ' Fakes ' and ' Blaes,' are applied to the strata.

Among terms occasionally used, the following may be mentioned :

Balls.—Nodular concretions of pyrites, ironstone, or limestone.

Blaes.—Soft clayey shale.

Callus.—Applied to hard caking deposit.

Clunch.—Tough or indurated clay or marl.

Fakes.—Shaly sandstone or sandy shale.

Galls.—Irregular cavities in stone, filled with ochreous or clayey material.

Galt or *Gault*.—Clay (irrespective of age).

Growan.—Decomposed granite.

Isinglass.—Selenite.

Kale.—Rubbly ferruginous sandstone or limestone.

Metal.—Pyrites.

Rag or *Ragstone*.—Hard shelly limestone.

Rubble.—Loose weathered rock.

Skillet.—Soft slate or shale.

Whinstone.—Dykes or sills of basalt or dolerite.

CHAPTER IX

THE WATER-BEARING STRATA OF BRITAIN, WITH ESPECIAL REFERENCE TO ENGLAND

IN the chapter on general geology reference has been made to the different kinds of rocks which yield supplies of water, and to the changeful character of geological formations, some of which may be fairly uniform over large areas, while others are composite and inconstant.¹

Of the more persistent formations of clay, limestone, or sandstone, we may mention the Keuper Marls, also the Lias, Oxford, Kimeridge, Weald, Gault, and London Clays; the Carboniferous Limestone and the Chalk; and the Bunter and Keuper Sandstones.

With the more mixed formations we may group the Middle Lias, the Inferior and Great Oolite series, the Corallian, Portland Beds, Lower Greensand, Woolwich and Reading Beds, Oligocene and Alluvial deposits.

PRINCIPAL WATER-BEARING FORMATIONS.

PLEISTOCENE	...	Gravels.
PLIOCENE	...	Crag Deposits.
OLIGOCENE	...	Headon Hill Sands.

¹ For particulars relating to Great Britain and Ireland, the Memoirs of the Geological Survey should be consulted, and especially the Memoirs on Water-Supply of English Counties. (See Appendix.)

EOCENE	...	Barton and Bagshot Sands. Oldhaven and Blackheath, Woolwich and Reading, and Thanet Beds.	
CRETACEOUS	...	Chalk. Upper Greensand, Lower Greensand. Hastings Beds.	
JURASSIC	...	Portland Beds. Corallian. Great Oolite Series. Inferior Oolite Series. Middle Lias.	
TRIASSIC	...	Keuper and Bunter Sand- stone.	} NEW RED SANDSTONE SERIES.
PERMIAN	...	{ Magnesian Limestone. Permian Sandstone.	
CARBONIFEROUS		Coal-Measures (Sandstones). Millstone Grit. Carboniferous Limestone Series.	
DEVONIAN AND OLD RED		SANDSTONE.	

While all these formations are water-bearing, their capacities for yielding good supplies are exceedingly variable, and in some cases may locally be reduced to the lowest limit. It is necessary, therefore, to give attentive study to each formation at the locality where a water-supply is required, and not to trust to general descriptions.

RECENT AND PLEISTOCENE.

Blown Sands.—Extensive tracts of Blown Sand are met with along many parts of the coast, and sometimes inland, and supplies of fresh-water are often obtained in shallow wells. In Cornwall, where the sand is

largely composed of comminuted shells, the water is hard.

Shingle.—Large accumulations of shingle may yield supplies of fresh-water. The shingle tract at Dunge Ness is an example. Good and permanent supplies of soft-water are there obtained, except along the sea-margin, where salt-water is apt to be drawn in by pumping.

At the Bungalow Town situated on the shingle beach at Shoreham in Sussex, water is partly obtained from rain-water, and partly by carrier from Shoreham.

Alluvium.—This term is applied to the bottom lands, the flat meadow and marsh lands that border most rivers and estuaries, and include all tracts 'liable to floods.'

Composed largely of silt (fine sandy loam or inundation mud), with intercalations of peat, shell-marl, clay, sand, and gravel, its components are liable to rapid changes in thickness. In mass the Alluvium may be from 10 to 80 feet or more in depth.

Water may be obtained from some of the porous beds of sand and gravel, which may or may not be directly connected with the river. If required for drinking purposes, it is desirable to shut out the surface-water and draw from gravel when at a depth of 6 feet or more. In a broad tract of Alluvium porous beds may be fed by land-springs, and water may rise above the ordinary river-level. (See p. 58.)

As a rule the water from Alluvium is not to be recommended, especially in the neighbourhood of large towns and cities.

Along the marshlands of the Thames below Barking, and in those of East Lincolnshire and other parts of the Fenland, the water from Alluvial deposits is more or less saline; and cottages have been supplied from ponds and ditches, or with rain-water collected from roofs.

Along the borders of the Ouse Valley, above King's Lynn, the soil and subsoil are saline, and few of the shallow wells yield good drinking-water. It has been stated that where the amount required is not very great 'a fairly palatable water is obtained by mixing one pailful of well-water with two of rain-water.'¹

Peat absorbs water readily, and on moorland areas large quantities of water are stored in peaty ground, whence springs issue, as on the Longmynd and other regions.

Valley Gravel and Brickearth.—Deposits of gravel and sand with brickearth or loam are found in most river valleys at a higher level than the Alluvium; and, as in the case of the Thames Valley, they extend over wide tracts, with a thickness of from 5 to 50 feet, and in some districts much more.

In the gravel and sand water is almost everywhere to be found, at or about the level of the river when the deposits extend to a depth below that level, and at higher positions if there are terraces or underlying platforms of impervious strata.

Water drawn from the lower levels, like that obtained from deposits of Alluvium, may be directly connected with the river, and wells from which a large amount of water is pumped would draw upon the river, with the

¹ 'Climates and Baths of Great Britain,' 1902, p. 113.

benefit of intermediate filtration. It will be hard or soft according to the character of the river.

The water should of course be taken from the valley above the town or village to be supplied.

In the Vale of Pickering, as noted by C. Fox Strangeways, there are superficial deposits of sand, gravel, and clay, overlying Boulder Clay and Kimeridge Clay, and in them water, sometimes of an artesian nature, is obtained at depths of 50 to 100 feet.

The gravels at a higher level would be fed by direct rainfall, and in certain cases by land-springs. Here the amount to be obtained would vary according to the form of the ground and the thickness of the gravel, much depending on whether the gravel occurs in one sheet over a considerable tract, or is intersected by streams that have cut channels down to an impervious stratum, whereby much of the supply of water would be drained off.

In the neighbourhood of Oxford, where the valley gravels are largely composed of limestone-pebbles, the water is hard. Such gravels occur over considerable areas in the Oolitic districts of the Midland counties, and their 'piped' surfaces, as near Bedford, indicate the dissolution of the calcareous stones.

In old times London was largely supplied from wells in the gravel, but these gradually became polluted, and all have been abandoned. At the present time, in the more densely populated areas that are mostly covered with buildings or paved, the gravel receives comparatively little of the rainfall.

The old Aldgate Pump, which originally derived its water from local sources, has since 1876 been supplied from the New River.

At Bedford a considerable amount of water pumped from the Great Oolite is derived from the rainfall on the valley gravels, and indirectly from the river. (See p. 192.)

Lower down the course of the river, north of St. Neots, supplies are obtained from the valley gravels, by means of a well 30 feet deep. At Tonbridge, at Haverfordwest, and other places, water for the town supplies is obtained from valley gravels.

Tunnels or adits have been driven in alluvial gravels below the plane of saturation for the supply of Montrose, Perth, and Derby. At Derby the filter tunnels alongside the River Derwent are about 18 feet deep in the gravel. (See also p. 124.) Cork has been supplied from a tunnel excavated in the alluvial gravels along the Lee Valley, more than a mile above the city. The tunnel is parallel to the river for about 366 yards, distant 25 feet from the northern bank, and from 15 to 20 feet below the surface of the Alluvium. A supply of 4 million gallons daily is obtained, and it is derived from the gravels below the level of the river, and not by direct lateral percolation.¹

Glacial Drift.—This mixed formation comprises considerable tracts of water-bearing sands and gravels, which have yielded supplies to numbers of villages in the Midland and Eastern counties of England, as well as elsewhere.

Associated with the Drift there are extensive sheets and smaller patches of tough impervious Boulder Clay and a good deal of loam. Gravel and sand are found

¹ J. R. Kilroe, in 'Geology of the Country around Cork,' *Mem. Geol. Survey*, 1905, p. 114.

intercalated in Boulder Clay as well as above and below that clayey accumulation. Where above the clay limited supplies of water are obtained, and from the intermediate beds the supply is sometimes of an artesian character. (See Fig. 28, p. 127.)

In sinking or boring through Boulder Clay, much uncertainty must in all cases exist with regard to depth and to the presence or absence of underlying sands and gravels.

The Boulder Clay may vary in thickness from a few feet to 150 feet and more. It rests sometimes with great evenness on the strata below, but often extends irregularly to considerable depths; and it may be found directly on an impervious foundation, such as the London Clay, without the intervention of the sands and gravels which outcrop beneath it along the borders of a not far-distant river valley.

Where Boulder Clay rests on Chalk, there may be justification in proceeding with a boring when an unusual thickness of the clay and associated gravelly drift has been met with. Such was the case at Glemsford in Suffolk, where the writer, in the full belief that the Drift must soon come to an end, gave encouragement to the well-borers. The boring was carried through 51 feet of gravel and sand, when Boulder Clay was reached, and this proved to be 218 feet thick. Beneath, a further thickness of 201 feet of sand and gravel, belonging to the Glacial Drift, was penetrated before the Chalk was reached at a depth of 470 feet. The boring was continued about 40 feet in the Chalk, when water was tapped, and it rose 2 feet above the surface, at the rate of 30 gallons a minute. A supply of 80 gallons a minute was raised by pumping, when

the water-level was lowered to 5 feet beneath the surface.¹

Such deep channels filled with Drift may arrest the underground flow, and in some cases impound the water on one side. They have been met with near Hitchin, near Newport in Essex, and elsewhere. In some parts of Norfolk there is great uncertainty of supplies of water owing to the disturbed condition of the strata, known as the Contorted Drift. Thus, the quality, amount, and level, of the water in Drift areas may vary to a considerable extent within a limited district. The Contorted Drift contains large transported masses of Chalk, such as might be capable of yielding small supplies of water; and Mr. A. C. G. Cameron has described an immense mass of Chalk which occurs in the Boulder Clay of Huntingdonshire. The village of Catworth, about ten miles west of Huntingdon, is based on this Chalk, and a well at the Manor Farm derives a never-failing supply of water from the bed, which is there 12 feet thick. Still thicker masses of transported clay have been encountered in the Boulder Clay of the Eastern counties. At a brick-yard at Fodderstone Gap, between Shouldham and South Runcton, in West Norfolk, a well was sunk 50 feet through a mass of Kimeridge Clay that rested on Lower Greensand, and was clearly a boulder, as described by Mr. Clement Reid.

More recently, a well sunk two miles S.S.E. of Biggleswade Railway-station proved the following strata, as described by Mr. Henry Home in 1903:

¹ See Whitaker, 'Water-Supply of Suffolk,' 1906, p. 58.

Well at Biggleswade.					Thick- ness.	Depth.
					Feet.	Feet.
Soil					2	2
Boulder Clay					8½	10½
Glacial Drift	{	Dark clay with septaria; trans- ported mass of Ampthill Clay			67	77½
		Chalky Boulder Clay			6	83½
		Fine silty clay, with chalk and a few boulders			10½	94
		Clay, disturbed in upper part			15	109
Gault ...		Sand			71½	180½
Lower Greensand	}					

Such a thick mass of transported clay might in some situations have deterred further sinking, as the fossils clearly indicated the age of the clay, and it might have been presumed that some 400 feet of Oxford Clay occurred directly below. Further sinking, however, proved that the mass of Ampthill Clay had been incorporated in the Glacial Drift.

The yield of water from the Lower Greensand was very large. (See p. 176.)

In the hilly and mountainous regions of the North of England, Wales, and Scotland, much of the Boulder Clay is an earthy and stony Drift, more or less pervious, and passing into gravel and sand. In Cumberland the Drift attains a thickness of 200 feet in places.

Wells in Boulder Clay sometimes yield a sufficient amount of soakage-water for a cottage. As a rule, in the Eastern counties the Boulder Clay tends to keep much of the rainfall from the porous strata. (See Fig. 40.)

In the area south of the Thames there is no Boulder Clay, and the geological formations as a rule exhibit a greater thickness of subsoil or weathered rock-débris, which often serves as a filtering medium for surface impurities.

Plateau Gravels.—The plateau gravels, though often of little thickness and limited extent, have in old times yielded useful supplies for small villages and mansions. Some varieties of the gravel have a matrix so clayey that they are practically impervious, and hold up water ; such is the case with some of the pebbly gravels north of London, as at Totteridge.

PLIOCENE.

These deposits in the Eastern counties comprise the following subdivisions :

- Forest Bed Series.
- Norwich Crag Series.
- Red Crag.
- Coralline Crag.

The **Forest Bed Series**, which extends but a short distance inland, from a little west of Cromer to Kessingland, south of Lowestoft, consists of gravel, sand, and clay, with peaty beds, and is from 6 to 20 feet thick. It is intimately linked with the underlying Crag Series, but is of no importance as a water-bearing formation.

The **Norwich Crag Series**, from 30 to 150 feet thick or more, consists of pebbly gravel and sand, with shell-beds and impersistent bands or 'jams' of laminated clay (Chillesford Clay). Good supplies of

water may be obtained locally, but here and there the presence of lignite or peaty beds and impure silt has given the water an unpleasant smell. Over considerable areas the deposits rest directly on the Chalk, and the water, when not upheld by clay-bands, may be connected with that of the underlying formation.

Red Crag.—This formation, intimately connected with the Norwich Crag, consists, when exposed at the surface, of red and usually shelly sands, with much current-bedding. At a considerable depth the Crag is grey. In a boring at Saxmundham 105 feet of Crag was passed through, but the ordinary thickness is from 25 to 40 feet.

Mr. Whitaker has remarked that at the junction of the Crag and London Clay in Suffolk there are springs, many of which have been used for water-supply. The Crag being highly ferruginous, the water is liable to be chalybeate.

Coralline Crag.—This formation consists of pale buff shelly sands, which are sometimes hardened into stone-beds that have been used for building purposes. The thickness is from 40 to 80 feet in Suffolk, where the strata are exposed over a limited area. Aldeburgh is supplied from a well and trench dug in the Coralline Crag.

The waters from the Crag formations would be moderately hard.

OLIGOCENE.

The **Fluvio-marine or Oligocene Series** occurs in England chiefly in the Hampshire Basin, in the northern half of the Isle of Wight and bordering tracts of the mainland.

Taken as a whole, the strata consist of an alternating series of shelly clays, marls, bands of limestone and sands.

The succession is as follows :

	Approximate Thickness.
Hamstead Beds (clays, loams, and marls)	260
Bembridge Marls (clays and marls with limestone)	100
Bembridge Limestone	10
Osborne Beds (marls, clays, and shales, with limestone and sandstone)	100
Headon Beds (clays with limestone and sands)	150

The supplies of water are limited and uncertain, and not always of good quality.

Small supplies have been obtained from the Headon Beds, Osborne Beds, and Bembridge Limestone. Cowes has been in part supplied from a well in the Headon Beds.

EOCENE.

The **Bagshot Series** includes the following subdivisions :

Barton Sands.
Barton Clay.
Bracklesham Beds.
Bagshot Beds.

In the Hampshire Basin the Barton or Headon Hill Sands are so fine in grain that they do not freely yield water, but they attain a thickness of from 140 to 200 feet.

The Barton Clay is from about 160 to 250 feet.

The Bracklesham Beds consist of greenish sands and clays, the estimated thickness of which is 155 feet on the western and 650 feet on the eastern side of the Isle of Wight.

It is considered probable that these strata replace to some extent the Bagshot Sands of the Island, that are reckoned to be 660 feet thick on the west, where they contain intercalated beds of clay, and only 100 feet on the east. They yield supplies of water at different horizons, uncertain in quantity, and not always good in quality.¹

The Bagshot Series in the London Basin comprises the Barton Sands (or Upper Bagshot Sands), reckoned to be from 100 to 300 feet thick, and consisting mostly of yellow quartzose sands.

Underlying them are the mixed Bracklesham Beds, greenish sands, loams, and clays, with lignite and iron-stone, that attain a thickness of from 40 to 60 feet.

At the base are the Bagshot (or Lower Bagshot) Sands, which consist mainly of fine yellow quartzose sands, with seams of white pipe-clay, and near Brentwood in Essex with flint pebble-beds in the upper part. The beds generally pass downwards by alternation of sand, loam, and clay, into the London Clay. The thickness varies from about 50 to 120 feet. The Bagshot and Barton Sands are the principal water-bearing strata in the Bagshot Series of the London Basin, and the water is soft.

Dr. A. Irving has remarked that the Bagshot Series of Berkshire, Surrey, and Hampshire, yields water, which, although free from the hardness due to calcic carbonate, 'is highly charged with certain salts of iron, which, by oxidation on exposure to the air, yield an ochreous red precipitate.' Moreover, the water some-

¹ See 'Geology of the Isle of Wight,' *Mem. Geol. Survey*, by H. W. Bristow; 2nd edit., by C. Reid and A. Strahan, 1889, p. 101.

times causes 'the rapid corrosion of iron pipes in which it is conveyed.'

The greenish sands of the Bracklesham Beds at a distance from the outcrop yield water that is apt to be contaminated with 'noxious carbonaceous matter,' and to have an unpleasant odour. Even the underlying Bagshot Sands are liable to be affected in the same way, the best water in some localities being obtained from the sands overlying the Bracklesham Beds, now generally known as the Barton Sands.¹

In some tracts of Hampshire the Barton Sands, as remarked by Mr. H. J. Osborne White, 'are practically waterless, as the absorbed rain quickly sinks through their loose sands into the beds below.'²

The **London Clay** comprises in the London area a great thickness of impervious clay, brown at the surface, bluish-grey below. Its upper part, forming a passage into the Bagshot Beds, comprises alternations of clay, loam, and sand, beneath which is the mass of clay with bands of septaria or cement-stone. The Basement-bed consists of a variable thickness of sand with flint-pebbles, and occasional bands of hard calcareous sandstone. Locally it yields small amounts of water.

In the London Basin the thickness varies from about 450 feet at London to about 30 feet in the neighbourhood of Newbury, and still less farther west. The thickness in the Isle of Wight is from 230 feet on the west to 320 feet on the east.

The **Oldhaven and Blackheath Beds** occur between the London Clay and Woolwich and Reading Beds, over

¹ 'On the Bagshot Sands as a Source of Water-Supply,' *Geol. Mag.*, 1883, p. 404.

² 'Geology of Basingstoke,' *Mem. Geol. Survey*, 1909, p. 107.

parts of Kent, eastern Surrey, and the eastern part of the County of London.

They consist mostly of sand in the Oldhaven district near Herne Bay, and of pebble-gravel at Blackheath, Chislehurst, and Bromley. Local supplies of soft-water may be obtained from them.

The thickness of both sands and pebble-beds is very irregular, and varies from a few feet to 60 or 70 feet.

Woolwich and Reading Beds.—Local supplies are to be obtained from the sands and pebble-beds intercalated in the Woolwich and Reading Beds. The total thickness of the formation, which comprises also red and mottled clays and shelly beds, varies from about 15 to 90 feet in the London Basin, and in the Isle of Wight from 84 feet on the western to about 160 feet on the eastern side of the Island.

Under parts of northern London, where, in the absence of the Thanet Sands, the formation rests directly on the Chalk, it yielded supplies of water to some of the earlier artesian wells—water which was no doubt in connection with that of the Chalk.

Thanet Beds.—This formation consists of fine white, buff, or grey sands, somewhat argillaceous, and varying in thickness from a few feet on the west and north of London to 60 feet and more to the south and south-east. The strata have supplied water, not separable from that of the underlying Chalk, and, indeed, they have been regarded as, to some extent, feeders of the Chalk in the London Basin.

Where the basement portions of the Woolwich and Reading Beds consist of sands, it is difficult, and often impossible, to separate them from the Thanet Sands.

The Thanet Sands, being firm, are not fitted to yield a large and free supply, as circulation would be slow.

As an illustration of the strata passed through in the London Basin, the following record is given :¹

HOLLOWAY, ISLINGTON, ABOUT TWO HUNDRED YARDS
SOUTH OF THE CATTLE MARKET.

				Thickness.	Depth.
				Feet.	Feet.
Made Ground	...	...	...	20	20
London Clay	{	Yellow clay	...	12	—
		Yellow and blue clay	...	13	—
		Blue clay	...	103	148
		Mottled clay	...	26	—
Reading Beds	{	Yellow clay	...	7	—
		Yellow sandy clay	...	6½	—
		Yellow loamy sand	...	3	—
		Dead sand	...	6½	—
		Dead green sand	...	6	—
		Dark sand	...	7	—
		Sand and pebbles	...	12½	222½
Thanet Sand	{	Dead sand	...	3½	—
		Green sand, flints	...	1½	227½
Upper Chalk	{	Chalk	...	15½	—
		Chalk and flints	...	69	—
		Hard chalk	...	6	—
		Chalk	...	8	—
		Chalk and flints	...	39	—
		Chalk	...	6	—
		Chalk and flints	...	16	—
		Hard flint	...	1½	—
		Hard rock	...	¼	—
		Hard flint	...	½	—
		Chalk and flint	...	56¾	—
		Chalk	...	4	450

¹ Summary of Progress, *Geol. Survey* for 1906, 1907, p. 151.

A shaft was sunk 20 feet, and then a boring $8\frac{1}{2}$ inches in diameter was made by Messrs. Isler and Co. The height above Ordnance Datum is about 130 feet. The water-level was 210 feet down, and the minimum supply 3,500 gallons an hour.

CRÉTACEOUS.

The Chalk.—This formation of soft and hard white limestone with and without flints, with occasional bands of marl, and often a considerable thickness of it at the base, is regarded as the most important source of water in England. It extends over large areas, it attains a great thickness, and it readily absorbs water. Nevertheless, it does not freely part with its water, and to obtain a supply it is necessary that the well or boring should traverse one or more fissures. Fortunately, the Chalk as a rule has numerous tiny joints and many fissures.

For practical purposes the Chalk has been divided as follows :

- | | |
|--------|--|
| Upper | { Chalk with flints.
Chalk Rock (Wiltshire to Hertfordshire and Norfolk). |
| Middle | { Chalk with few or no flints.
Melbourn Rock (Southern and Eastern Counties).
Belemnite Marl. |
| Lower | { Grey Chalk.
Totternhoe Stone (Berkshire to Hertfordshire, Bedfordshire, Cambridgeshire).
Chalk Marl. |

In the south-east of England the total thickness varies from about 620 to 820 feet. In Norfolk it

amounts to 1,200 feet, and in the Isle of Wight to 1,766 feet.

There is a considerable unconformity between the Chalk and Eocene strata, so that the thickness of the Chalk is nowhere complete in this country, because whether covered by Eocene formations or exposed at the surface it has been subjected to more or less erosion. Nevertheless, there is seldom any marked discordance between the stratification of the Chalk and that of the overlying Thanet or Woolwich and Reading Beds.

Other subdivisions in the Chalk, based on the occurrence of certain assemblages of fossils, and known as *Zones*, are independent of lithological characters, and not, therefore, reliable as indications of water-bearing beds; but they may sometimes aid in calculating the thicknesses of the strata. The *Zones* are named from the occurrence of a particular species of fossil.

According to Mr. Whitaker, 'As a general rule there is more or less communication downward through the Upper and Middle into the Lower Chalk, so that the water in the Chalk may usually be treated as a whole.'¹

In some respects the Chalk Marl, which in a clayey form occurs through great part of the Chalk region at the base of the formation, is of most importance in holding up supplies of water. It is from 20 to 120 feet thick. Like other clayey formations, it is capable of imbibing a good deal of water.

The circulation of water in the Chalk has been the subject of considerable debate. In the Upper Chalk in particular many flints occur, not only as isolated nodules along the planes of bedding, but also in

¹ *Proc. Geol. Assoc.*, xvii., 1902, p. 366.

continuous bands known as 'tabular flints,' which extend for considerable distances. Again, there are oblique veins of flints. Undoubtedly, the underground flow of water is affected by these tabular and oblique veins, which serve to arrest or divert the currents, and thus account in some cases for differences in the local water-level. The planes of stratification, with their nodules of flint, are affected sometimes by a kind of horizontal jointing, which also facilitates the transmission of water.

The Chalk, again, may be hard and dense, or soft like putty, at different horizons, thus yielding little water except by seepage in a well.

At the surface the Chalk is often weathered into a rubble, and shattered and fissured to a depth of several feet; or it may be furrowed by pipes due to dissolution of irregular portions of the mass of the limestone, the hollows, mostly funnel-shaped, being filled with Clay-with-flints and gravel. (See p. 72.) In most cases rain is readily absorbed by the mass of the rock, and it descends through cracks and joints, pipes, and swallow-holes, to a plane of saturation limited by the physical features and geological structure. The storage capacity of the Chalk is great. On the high Chalk Downs the rainfall readily sinks into the ground except where there is a covering of the superficial accumulation known as Clay-with-flints, and this is not always impervious.

In Chalk districts there is an absence of running water except where deep valleys have been cut down to the plane of saturation, and this varies according to the inclination of the strata, the rainfall, and the elevation of the ground. (See pp. 52, 163.)

The underground flow is influenced by the geological structure, the general dip, and by undulations and faults in the strata ; but the movement is dependent on a natural outlet or on the effects of pumping. Thus, springs are given out along the west cliff at Eastbourne above the Belemnite Marl, the top of the Lower Chalk, as there is a south-westerly dip to the sea-coast, and there is in consequence little or no outflow of water on the slopes east of Beachy Head.

Springs are given out along the scarps, as along the North and South Downs, the Chiltern Hills, the Dunstable Downs, and elsewhere. Folkestone and Maidstone are in part supplied from Chalk springs ; Wisbech is supplied from a spring at Marham, south-east of Lynn.

Water is thrown out locally at various horizons, sometimes from the Chalk Rock ; notably at the base of the Melbourn Rock, above the Belemnite Marl, and more conspicuously at the base of the Totternhoe Stone above the Chalk Marl. In Cambridgeshire and Bedfordshire many a famous spring, utilized for water-cress beds, issues from the Totternhoe Stone. In Kent many springs issue from the Lower Chalk, sometimes, as noted by Mr. Whitaker from the base, where it rests on the Gault. It seems possible that, where they issue at the base of the outcrop of Chalk Marl, there has been some underground erosion of that bed.

Other springs are thrown out along the dip-slope of the Chalk, where the strata plunge beneath a covering of Eocene strata. Here the waters of the uppermost beds of Chalk are commingled with those of the Thanet Sands or with the sands in the Woolwich and Reading Beds ; and the streams to which they give rise course

over the clayey tracts of the London Clay, or filter through overlying valley gravels, as in the Wandle Valley north of Croydon.

Where the porous beds of Chalk above the Chalk Marl border the sea-coast, as along the coasts of Kent and Sussex, copious springs are thrown out at low-tide, the outflow being arrested as a rule by the sea-water at high-tide. Here the plane of saturation is regulated by the sea-level. At Lydden Spout, east of Abbot's Cliff, near Folkestone, as much as 3 million gallons a day has been recorded.

Along the borders of the Lower Thames, Chalk springs similarly issue at Erith and Northfleet, at Purfleet and Grays. In these cases the springs are to be regarded as the overflow of water partly due to local rainfall, but mainly to the underground flow from the rainfall respectively on the North Downs and on the Dunstable and Royston Downs. Excessive pumping in these tracts bordering the river or sea is apt to lead to an influx of sea-water into the wells.

It is probable that the outlets of the more important springs are along joints or fissures; and this explanation would apply to the Bournes, where the issue of water takes place at higher levels in a valley after prolonged rainfall. (See p. 73.) Without a concentration of water in a fissure the outflow would be more general along the slopes in the form of seepage.

The depth to which it is needful to sink in the Chalk uplands depends, of course, primarily on the ordinary plane of saturation, which is indicated by the outflow of springs, or by the stream in the nearest valley excavated in the Chalk. Estimates can be given of these depths. The saturation-plane is at a somewhat

higher level according to the shape of the ground ; and it may vary with the rainfall as much as 70 or 80 feet on the higher grounds.

It is, however, needful, as before noted, to sink or bore until a free supply is obtained from a fissure, and this is a matter that cannot be foretold. Under London, beneath the covering of Eocene strata and Drifts, it is necessary sometimes to bore as much as 300 feet or more in the Chalk before water is encountered, and in rare cases no free or sufficient supply of water has been met with throughout the formation.

Estimates can be given of the depth at which Chalk will be reached beneath coverings of Eocene and other strata ; but in the London area not only has the question of fissures to be borne in mind, but also the depletion of water by the great amount of pumping. Although the Upper Chalk has as a rule been mostly drawn upon for supplies of water, yet as regards fissures there is no evidence of any great difference between that division and the lower strata above the Chalk Marl. It has, however, been generally observed that in the deeper wells, beneath thick coverings of Eocene strata, the Chalk is less fissured than nearer the outcrop, and in consequence large supplies are not so readily obtained. This is but natural, as nearer the outcrop, especially on the borders of a basin, the strata are more likely to be shattered.

At great depths the pressure of overlying deposits has been regarded as likely to prevent the formation of fissures, and by keeping in air to retard the flow of underground water.

Concealed anticlines and faults may at a depth yield good supplies of water.

It is not often that large cavities or caverns are met with in the Chalk, but some have been noted by Prestwich at a depth of 270 feet at Knockholt, near Sevenoaks, and by Mr. S. Sills at Strood, near Rochester.¹ At Knockholt the cavern was 30 feet long, 12 feet wide, and 30 feet in height. At Rochester the cavity, an enlarged fissure, was found to extend for a distance of about 150 feet somewhat irregularly, and to be in places rather more than 12 feet wide and 17 feet in height.

Occasionally the surface-pipes descend to a depth of about 150 feet, and, being somewhat oblique, they may be passed through in a shaft or boring, so that ferruginous clayey matter has been met with in a deep Chalk well.

Analyses show that there is less calcium carbonate in solution in deep well-water, and therefore less dissolution of the Chalk. Other saline ingredients may be larger, and sodium carbonate is sometimes met with.

This was the case in the artesian waters pumped at Trafalgar Square, from the Chalk and Lower Eocene strata at a depth of nearly 400 feet. The water contained 68 grains per gallon, comprising 20 of sodium chloride, 18 of sodium carbonate, $13\frac{1}{2}$ of potassium sulphate, $8\frac{1}{2}$ of sodium sulphate, and little more than 3 of calcium carbonate. Some of these ingredients may have been derived from the Eocene strata.

A considerable amount of water is held in so-called dry Chalk by capillary attraction. Thus, 'One square mile of dry Upper Chalk, 1 yard in thickness, always contains nearly 3,500,000 gallons of water, and when saturated 200,000,000 gallons.'²

¹ *Geol. Mag.*, 1908, p. 192.

² J. T. Harrison, *Proc. Inst. Civ. Eng.*, cv., 1891, p. 5.

That fissures become enlarged by the circulation and pumping of water is again natural, the fact being due to the amount of calcium bicarbonate carried away in solution by Chalk springs and from wells. In width the fissures may vary from about $\frac{1}{2}$ inch to 2 or 3 inches or more, but they are usually less than 1 inch.

It was estimated by the late Sir John Evans that every square mile of a Chalk district loses about 140 tons of substance in the course of each year;¹ while it has been calculated that every million gallons of water drawn from the Chalk carries in solution on an average $1\frac{1}{4}$ tons of Chalk, thus giving additional storage-room for 110 gallons of water. This extra space, however, may be to some extent obliterated by slight subsidences.

Good supplies of water have been obtained from the Middle Chalk near Luton and Tring, and also at the Kenley and Caterham waterworks. At Richmond the entire thickness of the Chalk was penetrated, and no water was found below a depth of about 180 feet in the formation. At the Holloway Sanatorium, Thorpe, near Chertsey, the Chalk was reached in a boring at a depth of 525 feet, and penetrated for 275 feet, when the yield was less than 3,000 gallons per day.

In South Dorset and in Devonshire the Chalk is practically water-bearing throughout its mass, there being little or no development of clayey Chalk Marl at the base. In consequence the waters of Chalk and Upper Greensand are not to be separated. Again, in Norfolk, Lincolnshire, and Yorkshire, there are seldom any conspicuous beds of clayey Chalk Marl at the base of the formation.

¹ *Trans. Middlesex Nat. Hist. Soc.*, 1887, p. 11.

Wells sunk into the Chalk have a great advantage over borings in the facilities they afford for driving galleries.

The waterworks at Goldstone Road, Brighton, as remarked by Mr. Whitaker, 'are perhaps the best example of the right way of getting a very large supply of water from the chalk galleries, being driven (in one case to the length of 800 feet) at about low-water level, so as to cut the fissures and intercept the water on its way to the sea.

'The whole of the works (shafts and galleries) are in the White Chalk, with but few flints in the bedding-planes, but with many oblique layers along joint-planes. The supply comes chiefly from a few powerful springs, and, though small contributions issue between these, it is noteworthy how far a tunnel has sometimes been driven before reaching a fissure of large yield. Under these circumstances borings, or even shafts, might have failed to yield a large supply.'¹

J. Mansergh (1882) stated that the fissures were encountered about every 30 feet in some parts, and where farther apart the yield was greater. The level of the water-table at a distance of six miles from the coast was about 230 feet above low-water, the fall being about 38 feet per mile.

At Basingstoke and Broadstairs half a million gallons a day or more are obtained from wells and tunnels in the Chalk.

Croydon is supplied from several wells in the Chalk. One of these, south of Addington, was sunk 205 feet, with a diameter of 10 feet, and with galleries (6 feet high and $4\frac{1}{2}$ feet wide) having a total length of

¹ *Rep. Brit. Assoc.* for 1885.

813 yards, made chiefly about 150 feet below the surface. A number of fissures were cut through, one of which yielded 600,000 gallons a day. The total yield of the well after a wet season is estimated at $1\frac{3}{4}$ million gallons per day, and the minimum yield at about 1 million gallons per day.¹

A well at Docking in Norfolk, sunk to a depth of about 180 feet, through 140 feet of Boulder Clay, gravel and sand, and 40 feet of Chalk, ran dry many years ago. The well, of which particulars were recorded by Mr. G. Barrow, was deepened 10 feet, when a band of tabular flint was encountered in the Chalk. On breaking through this impervious barrier, water came in and rose rapidly, and the supply was maintained. The failure of the well may have given rise to the name 'Dry Docking,' which has been applied to the village.

On the Chalk uplands the expense of deep wells has been a drawback to the growth of population. Rain-water has been used for household purposes, and Dew-ponds have been constructed for cattle. These inconveniences have been remedied on parts of the North Downs by the establishment of Water Companies.

In the valleys the water is liable to pollution from villages.

A certain amount of danger may arise also from cemeteries and sewage-farms situated on the bare Chalk. The direction of the underground flow of water has to be considered in connection with wells that are near those sources of contamination. It is desirable also to observe the nature of the Chalk, as rapid per-

¹ H. V. Moss, *Croydon Guardian*, March 26, 1910.

colation is arrested sometimes by coverings of rubbly Chalk and marl beneath the surface soil ; such coverings act as filters on the flatter lands and more gentle slopes, and check the free access of water to fissured Chalk below.

Upper Greensand and Gault.—These formations, united under the general name of Selbornian by Mr. A. J. Jukes-Browne, to a certain extent replace one another on the east and west of the southern part of England.

Thus, at Burham and eastwards in Kent the formation beneath the Chalk and Lower Greensand is of the clayey type, known as Gault ; on the Blackdown Hills in Devonshire the entire formation is of the Upper Greensand type. Over the intermediate area we have the twofold division of Upper Greensand on Gault. In the north-west part of Norfolk the Selbornian is represented by the Red Chalk of Hunstanton, the equivalent of which extends through Lincolnshire to Speeton in Yorkshire.

From a water-bearing point of view the Red Chalk may simply be regarded as the base of the Chalk.

The **Upper Greensand** formation, when well developed, is capable of yielding good supplies of water, held up for the most part by the Gault.

In Berkshire, Surrey, Hampshire, and the Isle of Wight, it consists largely of calcareous sandstone (known as 'firestone' and 'hearthstone'), of malm-rock and chert (both siliceous rocks) and sand, and the water is usually hard.

In Wiltshire it comprises fine grey and greenish sands, with chert-beds in the upper part ; in Dorset,

Somerset, and Devonshire, the sands are capped by a greater thickness of chert-beds, and the water is soft unless the strata are covered by Chalk.

In the Blackdown Hills of Devon there is an occasional loamy base to the sands, but water is held up by the Lias, Rhætic Beds, and New Red Marls, across the outcrops of which the Upper Greensand extends.

Farther west there are outlying masses of Greensand on the Haldon Hills.

Taunton, Crewkerne, Shaftesbury, Bridport, Lyme Regis, Sidmouth, Dawlish, and Teignmouth (in part), are supplied by springs from the Upper Greensand.

In Devonshire the thickness of the formation is about 170 feet; in Dorset it varies from 45 to 160 feet.

Upper Greensand has been met with in some of the deep wells under the London district, at Kentish Town, Crossness, Richmond, and Streatham; but it is there of no consequence as a water-bearing formation.

In the Isle of Wight the thickness varies from 45 to 120 feet, in Hampshire it is about 80 feet, in Surrey from 40 to 50 feet, and in Sussex from 50 to 80 feet. In these Southern counties many wells are supplied from the formation.

Writing in 1898, Mr. Clement Reid remarked that Eastbourne had obtained a large supply of water from headings driven into the Upper Greensand at the Bedford Well, north of the town. The supply was greater than could have been expected from the Greensand, and the results of Mr. Reid's observations indicated that the well was sunk along a line of disturbance which brought shattered Lower Chalk against the Greensand, and let in a certain amount of water from

the pervious Chalk above. 'A dry season and the consequent lowering of the water-level by pumping caused, however, the influx of sea-water' along the fissured belt.¹

The **Gault** is a pale grey and blue, stiff, and often marly clay, with occasional sandy layers. It is well exposed beneath the Chalk at Folkestone, and it extends beneath the Upper Greensand from the western part of Kent to the neighbourhood of Lyme Regis. It occurs similarly through the southern and eastern-Midland counties to West Norfolk, being everywhere found below the Chalk, although the Upper Greensand dies out on the borders of Buckinghamshire and Bedfordshire. Both formations are replaced by the Red Chalk, as previously noted.

The thickness in Kent is from about 140 to 250 feet; in Surrey, Sussex, and Hampshire, from 100 to 180 feet; in Wiltshire 90 feet; under London from 130 to 200 feet; in Berkshire up to 260 feet; in Buckinghamshire 150; and in Bedfordshire 200. Thence the Gault diminishes to 90 feet in parts of Cambridgeshire, and from 20 feet in West Norfolk it gradually disappears as a clay-formation.

Lower Greensand.—This formation includes a great variety of rocks, and the subdivisions in the Isle of Wight, in the Wealden area, in the Midland counties, and in Lincolnshire, are distinct. The characteristic green sand occurs in places, and the mass of the formation is sandy, but the sands are of many colours, and sometimes pure white. Clays, beds of fuller's earth, chert-beds, and ferruginous rocks or ironstones, likewise occur.

¹ 'Geology of Eastbourne,' *Mem. Geol. Survey*, 1898, p. 13.

Although there is a broad outcrop on the southern side of the London Basin between Maidstone and Godalming, and considerable tracts occur on the northern side in the Woburn Hills and near Aylesbury, the beds do not extend beneath London. The Lower Greensand, however, forms one of the important water-bearing formations of England.

In the Wealden area the Lower Greensand has been divided as follows, in descending order :

Folkestone Beds.

Sandgate Beds.

Hythe Beds.

Atherfield Clay.

The basement Atherfield Clay, as regards water-supply, may be linked with the underlying Weald Clay. It is from 20 to 60 feet thick in the Wealden area, and from 60 to 80 feet in the Isle of Wight.

The *Folkestone Beds*, the highest division of the Lower Greensand, consist largely of sands, with occasional indurated masses of rock, which when ferruginous is known as 'carstone.' Fine white sands, suitable for glass-making, occur in many places. The thickness in Kent is from 90 to 130 feet, in Surrey 130 to 160, and in Sussex from 12 to 140 feet.

The *Sandgate Beds* are locally developed in Kent and eastern Surrey, but are not known at Godalming. They consist of clayey beds, with bands of sand and sandstone, and with the fuller's earth of Nutfield at or near the base. When present, these beds separate the water of the Folkestone Beds from that of the Hythe Beds; otherwise there is no marked division in the water-bearing strata of the Lower Greensand in the Wealden area. The thickness of the Sandgate Beds is

variable—100 feet in East Kent, 10 at Maidstone, 50 at Nutfield, 30 to 100 feet in Sussex and Hampshire. Locally some water is obtained from them.

The *Hythe Beds* include the well-known Kentish Rag, a somewhat siliceous limestone in Kent, where the water is hard; while westwards, in Surrey and Hampshire, the strata consist of sands, sandstones, and chert, with occasional clayey sands, and the water is soft.

Near Maidstone the Kentish Rag beds comprise alternating layers of rag and hassock (soft sandy and calcareous bands), the whole 30 to 35 feet thick. Where at the surface, these strata are so much jointed, piped, and fissured, that they are liable to receive contamination in populous districts. In places there are coverings of gravelly loam, and the pipes or fissures are infilled with the loam or brickearth, which may affect the circulation of underground water.

The thickness of the Hythe Beds is from 60 to 100 feet in Kent, 180 to 250 feet in Surrey, and up to 150 or 200 feet in parts of Sussex and Hants.

The following is a summary of some records of wells in the Lower Greensand of Surrey, published by Mr. Whitaker (1901 and 1905):

				Godstone.	Oxted.	Tatsfield.
				Feet.	Feet.	Feet.
Superficial Loam, etc.	...	...	...	—	—	10
Gault	...	...	...	—	—	56½
Folkestone Beds	...	...	...	96	62½	211
Sandgate Beds	...	...	...	38	30½	6½
Hythe Beds	...	...	...	38	152½	66
Atherfield Clay	...	...	...	—	4½	—
				172	250	350

In the borings at Oxted and Tatsfield the thickness of the Sandgate Beds was given with doubt.

In a well at Midhurst, made by Messrs. Le Grand and Sutcliff, a good supply of water was obtained at the depth of 100 feet, the water-level being 46 feet from the surface. The strata were as follows:

			Thickness.	Depth.
			Feet.	Feet.
Folkestone Beds	{	Sandy brown clay... ..	10½	—
		Ironstone	1	11½
Sandgate Beds	{	Sandy loam	11	—
		Dark sandy clay	3	—
		Light grey sand	19	—
		Yellow sand	7½	—
		Dark green clayey sand	8½	—
		Light green sand	14½	—
Hythe Beds	{	Dark green sandy clay	4	79
		Dark dead sand	2	—
		Yellow sandstone	19	100

Dorking, Sevenoaks, and other places, are supplied with water from the Lower Greensand.

In the Isle of Wight the Lower Greensand has been divided into—

Carstone	{	From about 320 feet in Compton Bay to 750 feet at Atherfield.
Sand-rock Series...		
Ferruginous Sands		

Atherfield Clay (60 to 80 feet thick).

The water-bearing beds above the Atherfield Clay are locally divided by clayey bands which throw out springs, sometimes of a chalybeate nature.

In the Isle of Purbeck in Dorset there are highly inclined beds of Lower Greensand.

In Wiltshire the formation, which is 25 to 30 feet thick, comprises very ferruginous sands and sandstones that have been worked for iron-ore at Seend. Beds of conglomerate also occur. Corsham is supplied with water from the Loxwell Springs on Bowden Hill.

In Berkshire limited tracts of Lower Greensand are exposed near Faringdon. The formation there consists of 25 to 40 feet of ferruginous sands and pebble-beds, with many fossils. Tracts of Lower Greensand occur also in the southern part of Nuneham Park and at Boar's Hill south-west of Oxford. On Boar's Hill water is obtained from wells 35 to 45 feet deep; the sands rest on an irregular surface of Kimeridge Clay, and more water is naturally obtained in the hollows.

In the Woburn district of Bedfordshire there is a considerable tract of Lower Greensand, which extends from Leighton Buzzard to Woburn, Ampthill, and Sandy. Consisting mainly of coarse and fine sand of various colours (the Woburn Sands), it includes also beds of fuller's earth and loam, pebbly layers and phosphatic nodules, and occasional beds of sandstone. The thickness is from 170 to 280 feet, and the formation has yielded good supplies of water.

Mr. A. C. G. Cameron has remarked that fuller's earth has a purifying influence on the water, and masses of the earth have been placed in wells to improve the quality of the water. He has also stated that 'Peaty water, and such as is otherwise turbid or discoloured, is clarified if run through a bed of it, and for that purpose it is carried by dealers round the marshlands and fen districts, where the inhabitants are largely dependent upon the drainage off the peat for their supply of water.'

About two miles south-east of Biggleswade a large amount of water (710 to 790 thousand gallons a day) was obtained from a shaft sunk to a depth of 180 feet through Drift and Gault, and $71\frac{1}{2}$ feet in Lower Greensand.

It is probable that a good deal of water enters the Lower Greensand from the Valley Gravels, which rest upon it farther north.

Occasionally the water is chalybeate, as at Flitwick, and sometimes wells have failed owing to thick coverings of Drift, which locally occur in the Woburn district.

In Cambridgeshire the Lower Greensand consists mainly of sands, with nodules of ironstone and some clayey or loamy beds. The thickness is about 70 feet. At Cherryhinton, Cambridge, according to Mr. H. F. Broadhurst (1908), 30,000 gallons of water per hour have been obtained from a 12-inch bore, at a depth of 200 feet, in the Lower Greensand, below the Gault. In other places also good supplies have been obtained.

In West Norfolk the Lower Greensand consists of sands locally hardened into a ferruginous sandstone known as Carstone. The thickness in the southern part is about 140 feet; farther north, at Sandringham, Snettisham, and Hunstanton, the formation, as described by Mr. Whitaker, comprises—

Carstone about 40 feet.

Clays and loams up to 30 feet.

Sands, with some stone-beds, 100 feet.

Good supplies of water have been obtained from the formation, and especially from the lower sands.

In Lincolnshire the 'Lower Greensand,' which in-

cludes beds probably of Purbeck - Wealden age, is divided as follows :

Carstone, consisting of sand, sandstone, and pebbly beds,
10 to 40 feet.

Tealby series, comprising limestone, clay, and iron-
stone, 10 to 225 feet.

Spilsby sandstone: sands, sandstone, and calcareous
pebbly grit, 6 to 50 feet.

Both Spilsby sandstone and Carstone have yielded good supplies of water.

The **Weald Clay** of the Wealden area attains a thickness of from about 500 to 800 or 1,000 feet, and is for the most part an impervious formation, although limited supplies of water for small houses have been obtained from hard bands of shelly limestone, or layers of sand and sandstone, as in the neighbourhood of Pulborough.

At Earlswood, Reigate, a thickness of 553 feet of Weald Clay was proved, and the underlying sands and clays failed to yield a supply of water.

The **Hastings Beds** comprise a variable series of sands, sandstones, and clays, grouped in descending order as follows :

Upper Tunbridge Wells Sand, with Cuckfield Clay.

Grinstead Clay.

Lower Tunbridge Wells Sand.

Wadhurst Clay.

Ashdown Sand passing down locally into Fairlight Clays.

All the sandy divisions locally contain impersistent beds of clay, and there is considerable uncertainty in

obtaining supplies of water. This is especially the case in the Ashdown Sand, where it appears at the surface, as well as where there is a thick covering of Weald Clay above it.

The fineness of some of the sands in the Tunbridge Wells Sands, which include also beds of sandstone, prevents free circulation of water.

The thickness of the Upper Tunbridge Wells Sand varies from 90 to 200 feet, the local Cuckfield Clay being about 15 feet.

The Grinstead Clay varies from 10 feet in thickness near Hastings, to 80 feet at Cuckfield.

The Lower Tunbridge Wells Sand is from 50 to 100 feet thick.

The Wadhurst Clay consists of clays and shales, with some bands of sand and nodules of ironstone at the base. It is of variable thickness, ranging from about 70 feet to as much as 267 feet at Hawkhurst.

The Ashdown Sand comprises sands and sandstones alternating with clays and shales, and passing down into a series of mottled clays and shales with sands, and sandstones known as the Fairlight Beds, and about 360 feet thick. The total thickness of the series is from 400 to 500 feet.

Cuckfield, Hastings, Tunbridge Wells, and other places, are supplied with water from the Hastings Beds.

The Wealden Beds in the Isle of Wight comprise a series of dark shales, variegated clays and sandstones, that attain a thickness of 700 or 800 feet where exposed. The full thickness is not seen. In Dorset the strata comprise an alternating series of sands, grits, and red and mottled clays, with a maximum thickness of about

2,000 feet, but this diminishes westwards to narrow limits. The beds are very highly inclined in places. Small supplies of water are to be obtained locally.

The 'ironsands' of Shotover Hill, near Oxford, which include fine white sands and some clay-bands, attain a thickness of about 50 feet; and the equivalent strata on the outliers of Muswell Hill and Brill, in Buckinghamshire, are now regarded as of Wealden Age. They yield water in wells, and springs are thrown out in places, but both sources at Brill have mostly become contaminated.

The strata outside the Wealden area include representatives of both Weald Clay and Hastings Beds.

CHAPTER X

THE WATER-BEARING STRATA OF BRITAIN (*Continued*)

JURASSIC—OOLITES.

THE Oolitic series includes some of the more important water-bearing strata in England: the Midford Sands and Inferior Oolite of the west of England, the Northampton Sands and Lincolnshire Limestone of Northamptonshire and Lincolnshire, the Great Oolite of Bath and the Cotteswold Hills, and the Corallian Sands and Limestones which extend between Weymouth and Oxford, and occur over considerable tracts in East Yorkshire.

Purbeck Beds.—This formation, which is best developed in the so-called Isle of Purbeck in Dorset, consists largely of marls, clays, and limestones, with subordinate sandy layers.

Supplies of water are yielded by the limestones in the Middle Purbeck division, where there is a series of stone-beds 80 or 90 feet thick ; but the limestones, being intercalated with clays, do not hold large amounts of water, nor can it freely circulate unless the rocks are fissured.

The same remarks apply to the Purbeck Beds in Wiltshire and elsewhere. Supplies suitable for cottages

and small houses may be obtained, but no large amounts of water are to be expected.

Portland Beds.—This formation, well developed in Dorset between Portland and Durlston Head, consists of a thick mass of shelly, chalky, and oolitic limestones, and of limestones with numerous nodules and bands of chert, about 90 to 120 feet thick; and of underlying sands with some nodular masses of calcareous sandstone and clay bands, 130 to 170 feet thick. The limestones are much jointed, and the water is sometimes separated from that of the sands below by clay-bands.

On Portland itself copious springs are given out in places, as at Fortune's Well and Southwell; but the area is naturally drained to such an extent that no abundant supply can be obtained by wells. A shaft and boring were made to a depth of 270 feet, and at first obtained a good supply, but sea-water was eventually drawn in.

In other parts of South Dorset, near the sea-coast, there is liability to draw in sea-water, so that the formation, though calculated to hold much water, only in certain places can be expected to yield good supplies.

The usual division of Portland Stone with underlying Portland Sands is applicable mainly to Dorset. In the Vale of Wardour in Wiltshire, the main mass of the formation consists of 60 or 70 feet of oolitic, chalky and shelly limestones overlying very sandy limestones, with at base 30 to 40 feet of sandy loams and clays.

The stone-beds are much fissured at the surface, and pollution has thus arisen in the neighbourhood of Tisbury. Where favourably placed, the strata should yield good supplies of water.

At Swindon the upper Portland Beds include sands

as well as limestones, 35 to 40 feet thick ; beneath them is a clay 14 to 20 feet thick, and at base sands and sandstones from 35 to 50 feet thick. The area of outcrop is, however, comparatively small, and the extensive quarries are likely to lead to some contamination of the water.

At Aylesbury the lower part of the formation consists of clay, known as the Hartwell Clay, which merges downwards into the Kimeridge Clay.

The exposed tracts are very limited, and this is the case also at Shotover Hill, near Oxford, at Brill and other outlying hills in Buckinghamshire. The upper beds consist of white limestones, with some clayey and sandy layers, 30 to 40 feet thick ; the lower beds comprise clays, and, near Oxford, also sands with large spheroidal masses of sandstone, or 'doggers.' The full thickness of the lower beds is about 20 feet. Numerous springs are given out at or near the base of the formation, above the Kimeridge or Hartwell Clays.

Kimeridge Clay.—This formation consists mainly of black shale and clay with nodules and bands of cement-stone. These nodules, or septaria, sometimes contain water when broken, and they have been termed 'water-stones.'

In thickness the formation varies from about 100 feet in the neighbourhood of Oxford, and 120 feet near Cambridge, to about 1,200 feet on the Dorset coast and in the Subwealden boring near Battle. In Lincolnshire and Yorkshire the Kimeridge Clay is 300 or 400 feet thick.

Although for all practical purposes it is an impervious formation in England, the shale is sometimes hard, and springs issue along joints and faults ; moreover, wells

have in a few instances obtained water that issued (perhaps through joints) along the planes where septaria occurred. Thus, a boring made at Downham Market by Messrs. Isler and Co., and recorded by Mr. Whitaker, was carried through 29 feet of Lower Greensand into the Kimeridge Clay as follows:

				Depth in Feet.
Kimeridge Clay, 187 feet	{	Rock	... ..	2
		Blue clay	... ..	72
		Rock	... ..	6
		Blue clay	... ..	99
		Blue clay with stone	... ..	6
		Blue clay	... ..	2

The water-level was 35 feet down, and the yield 360 gallons an hour, presumably from the bands of rock (? septaria or cement-stones).

In Scotland strata of the age of the Kimeridge Clay occur along the coast north and south of Helmsdale in Sutherland, and springs are given out in many places from beds of sandstone that alternate with shales and coarse conglomerates.

Corallian.—This formation consists in large measure of water-bearing limestones and sands, but it exhibits great variations in lithological character when traced across the country from Dorsetshire to Lincolnshire and Yorkshire.

In South Dorset, at Weymouth and Osmington, the beds consist in downward succession of a series of grits and iron-ore, clay, shelly and oolitic limestones, grits and sands, clay, and grit; the subdivisions varying much in thickness, but the total being about 200 feet. The chief water-bearing strata are the shelly and oolitic limestones 60 to 70 feet thick, that may yield from

8,000 to 70,000 gallons of water a day. Small amounts of water are obtained from the grit-beds at three horizons.

In northern Dorset, near Sturminster Newton, the Corallian beds are from 100 to 120 feet thick. The top beds consist of sandy loams, clays, and occasional ferruginous beds, about 20 or 30 feet; below there are about 50 feet or more of water-bearing limestones and marls; and at the base 20 to 40 feet of sands with bands and nodular masses of sandstone (Calcareous Grit) and occasional clayey bands. The water-bearing limestones are subdivided by marls, but the basal sands also yield water.

In Wiltshire the succession is much the same as in North Dorset, the thickness being about 100 feet at Westbury, but not more than 30 or 40 feet near Swindon. Thence to Oxford the Corallian formation consists of an upper division of coral-rag beds and limestones with sandy and clayey layers, 20 to 30 feet thick, and a lower division of Calcareous Grit and sands from about 10 to 30 feet thick. At Wheatley there is about 40 feet or more of shelly and oolitic limestone, which is extensively quarried. Unfortunately, rubbish is shot in the town quarry on to strata that yield supplies of water to some houses in the village.

To the north-east of Oxford, and thence through Bedfordshire to Cambridgeshire, the stone-beds and sands are absent, or so attenuated as to be of little use as water-bearing strata. The formation is, in fact, represented almost wholly by clay known as the Ampthill Clay, about 25 to 60 feet thick. Hence we find a considerable mass of clay, probably as much as 600 or 700 feet in places, above the Great Oolite series,

including the Oxford Clay, Ampthill Clay, and Kimeridge Clay, in parts of Buckinghamshire, Bedfordshire, Cambridgeshire, West Norfolk, and Lincolnshire. Water obtained at a depth below such a mass of clay is apt to have an accumulation of saline ingredients, to say nothing of the expense of trial borings. Many cottages and some villages in these clay-areas are dependent on rain-water, or on shallow wells; and supplies are limited, and not always good.

In the great area of clay just mentioned there is, however, one exception: at Upware, near Ely, where the rock-beds, oolitic and shelly limestones, appear as an inlier over a small tract (see Fig. 4), but they are not met with again northwards until we enter Yorkshire. There are also occasional rock-bands in some localities at the base of the Ampthill Clay, which may supply the needs of a cottage, as at Elsworth, where there is one band about 7 feet thick.

The Corallian rocks of Yorkshire outcrop over an area estimated by C. Fox Strangways at about 175 square miles, and yield many springs. In the Tabular Hills some of these have been utilized since very early times by means of artificial water-courses for the supply of farms and villages. The greatest thickness of Corallian in that region is at Kirkby Moorside, where the series comprises grits and limestones reckoned to be 370 feet thick.

Scarborough is supplied from springs and wells in the Corallian rocks. As noted by Strangways, there is a large spring at Cayton Bay which discharges about one million gallons a day. It issues from the Lower Corallian rocks where faulted against the Oxford Clay.

This source proving insufficient, a well was sunk at Osgodby into the Lower Corallian, with headings for a length of 70 yards. It is situated south-west of the Cayton Bay spring, and nearly on the line of strike of strata whence the spring issues. The pump at Osgodby can raise 864,000 gallons a day. It exhausts the well in dry seasons, but not in wet, and yet it does not affect the flow of the Cayton spring. A further supply of water was subsequently obtained at Irton, where the Corallian strata on the northern margin of the Vale of Pickering are faulted against the Kimeridge Clay. (See Fig. 32.) The boring was carried to a depth of 428 feet through superficial beds, Kimeridge Clay, and the entire Corallian series, into the upper part of the Oxford Clay. Water was discharged at a rate averaging one million gallons a day, and it rose, when first tapped, 10 feet above the surface. The gathering ground has been estimated by Strangways to occupy an area of 25 or 30 square miles.

In the north of Scotland, at Brora in Sutherlandshire, the Corallian strata are represented by hard sandstones and sands that are capable of yielding good supplies of water.

Oxford Clay.—This formation consists of a thick mass of clay and shale with nodules of cement-stone, or septaria, often of large dimensions. In thickness it varies in England from about 300 to 500 feet, and is for the most part wholly impervious. Near St. Neots in Huntingdonshire it comprises within a thickness of 60 feet six bands of limestone, one known as the St. Neot's Rock being 11 inches thick. Small supplies of soakage water might be obtained from this local series.

In Yorkshire the Oxford Clay varies from 20 to 150 feet in thickness.

At the base of the Clay, however, there is a subdivision known as the Kellaways Beds, which consist of alternating clays, loams, and sands. The sands are often indurated into hard layers, or huge spheroidal masses, or doggers, of calcareous sandstone. This lithological subdivision varies from a few feet up to 100 feet in Yorkshire, but the full thickness is not more than 75 feet in other parts of England. In the Southern counties there is usually 10 or 12 feet of Clay at the base of the sandy series above the Cornbrash.

The stony layers in the Kellaways Beds are too thin in Dorset to be water-bearing, but in Wiltshire and Oxfordshire they are locally more developed, and in Bedfordshire, and northwards through Northamptonshire, Lincolnshire, and Yorkshire, many springs are thrown out, and the strata are capable of yielding supplies of water.

Unfortunately, in the Midland counties the water is rarely of good quality; indeed, from the Vale of Blackmore in Dorset to Melksham, Oxford, and Bedford, saline waters have frequently been encountered beneath the Oxford Clay.

Cornbrash.—This formation in the south-west and western-Midland counties of England consists at its outcrop of rubbly and much-fissured limestones with marly partings, and is from 15 to 25 feet thick. It readily yields supplies of water for cottages, though liable in many cases to fail in times of drought. The outcrop is marked by many villages, but not a few of the shallow wells have become subject to contamination.

Where covered by Oxford Clay and Kellaways Beds

(with clay at base), the Cornbrash is hard and compact, and the fissures are not sufficiently prominent to yield much water.

In Bedfordshire the Cornbrash consists in places of a single band of nodular limestone, and elsewhere is but 2 or 3 feet thick.

Farther north it again becomes a prominent band, and extends through Northamptonshire with a thickness of about 15 feet, but diminishes in thickness in Lincolnshire; while in Yorkshire it is represented by ferruginous limestone and shale not more than 2 feet thick, and has only been recognized along the northern outcrop of the Great Oolite Series (Upper Estuarine) from the neighbourhood of Filey, northwards and westwards.

GREAT OOLITE SERIES.

The Great Oolite Series, below the Cornbrash, is subject to great changes when traced through the country from Dorset to Yorkshire, and the following subdivisions have been made:

South-Western Counties.	Midland Counties and Lincolnshire.	Yorkshire.
Forest Marble and Bradford Clay.	Great Oolite Clay.	} Upper Estuarine Series.
Great Oolite with Stonesfield Slate locally at base.	Great Oolite Limestone.	
Fullonian (Fuller's Earth formation).	Upper Estuarine Series.	

The **Forest Marble** consists largely of clays and shales, with beds of false-bedded oolitic and shelly

limestone 15 to 25 feet thick, and occasionally beds of sand with indurated masses of sandstone, as at Charterhouse Hinton, near Bradford-on-Avon. The free circulation of water is impeded often by the alternation of clays with flaggy limestones, and the inconstant character and thickness of the oolitic limestones and other porous beds, so that there is no great store of water over large areas. In some localities good supplies have been obtained, but for an abundant yield it is usually necessary to penetrate to the Great Oolite below, where that is present. As a rule the porous beds will yield supplies for a small house, and headings might increase the amount, but these might have to be supported owing to the irregular character of the strata.

In Dorset, where the Great Oolite is absent, the Forest Marble rests on the Fuller's Earth formation, mainly marl and clay. The water-bearing stone-beds are, however, well developed in many parts, from the neighbourhood of Bridport onwards to North Wiltshire, where the Great Oolite appears. At Bradford-on-Avon the basement portion of the Forest Marble consists of clay with a rich fossil-bed, known as the Bradford Clay—a somewhat impersistent layer met with at intervals from the Dorset coast to West Kington and Kemble in Gloucestershire.

On the Dorset coast the thickness of the formation is 80 or 90 feet; near Sherborne it is 130 feet; in North Wiltshire, 60 to 80 feet; at Cirencester, about 100 feet; and the thickness diminishes in Oxfordshire to 25 feet and less. Near Bicester the formation is mainly clay, and ceases to be water-bearing. To the north-east it passes into Great Oolite Clay.

The **Great Oolite Clay** consists of black, greenish, and coloured clays, with selenite and nodular ironstone in many places at the base, and also occasional sandy layers. The thickness is from 5 to 40 feet, and the formation extends from Buckinghamshire to Lincolnshire, but it is not water-bearing.

The **Great Oolite**, which appears near Bradford-on-Avon, extends through Bath and adjacent parts of Wiltshire to Minchinhampton and other parts of the Cotteswold Hills, where it is for the most part permeable and a good water-bearing formation.

Its thickness varies from about 40 or 50 feet near Bradford-on-Avon to 160 feet at Tetbury, and about 100 feet in the eastern Cotteswolds.

In the stone-workings or mines at Box water is met with in the lower ragstones beneath the oolite; but the mines are not troubled with serious water, as the deep valleys drain off the supply in springs. Towards Corsham the amount of underground water naturally increases. This flows along the planes of bedding.

On the uplands near Bath there are numerous springs, copious enough after rain, but in many cases the water is drained off rapidly. Larger underground supplies are to be expected farther north, where there are broader tracts of the formation, and especially where the full thickness occurs near or beneath coverings of Forest Marble. At Tetbury, again, much water is drained away by deep valleys. (See p. 196.)

The Avoncliff springs near Bradford-on-Avon have yielded as much as 120,000 gallons of water per day.

Near Bath there are springs which yield from 100,000 to 200,000 gallons of water a day; at Stroud there is a

spring yielding 500,000 gallons a day; and near South Cerney in Gloucestershire there is a spring yielding upwards of 1 million gallons per day.

At a distance from the outcrop at Chippenham, beneath the Cornbrash and Forest Marble, 150,000 gallons per day have been obtained by boring; in the railway-tunnel near Badminton 70,000 gallons per day were pumped from below Forest Marble; while from a well at the Thames Head near Cirencester as much as 3 million gallons a day have been pumped.

When we pass from the eastern side of the Cotteswold Hills into the Midland counties, from Oxfordshire into North Buckinghamshire, Bedfordshire, Northamptonshire, and Lincolnshire, the water-bearing capacity of the formation is much restricted by bands of marl or clay, alternating with hard white and grey shelly limestones. Springs are given out at various horizons, but the underground circulation is impeded.

In the plateau north of Woodstock the area of Great Oolite, though formed chiefly of limestones, contains from 25 to 33 per cent. of clay or marl, and there is seldom more than 10 or 12 feet of limestone undivided.

The ornamental waters at Glympton and Blenheim Parks are based on the Great Oolite, the streams carrying a good deal of mud.

At Stonesfield, as noted by the Rev. J. C. Clutterbuck, three distinct horizons of water are encountered at depths of about 15, 50, and 100 feet, the lowest only yielding a large amount of water.¹ This would, however, be derived from the Inferior Oolite above the Upper Lias Clay.

The Great Oolite in this district decreases from 80 or

¹ *Journ. R. Agric. Soc.*, ser. 2, i., p. 286.

100 feet to 42 feet at Bicester. Good supplies of water are locally obtained in North Buckinghamshire and elsewhere to the north-east, at or near the outcrop of the formation, where the strata are fissured. Sometimes, however, the fissures are filled with clay from the overlying Great Oolite Clay.

At Bedford, where the Great Oolite is from 22 to 30 feet thick, as much as 1 million gallons of water a day have been pumped from a well with headings adjacent to the river, but having no direct connection with it. As the River Ouse flows over the Great Oolite for some distance, there can be little doubt that the strata are fed to a considerable extent by fissures connected with the porous bed of the river, because the direct rainfall on the outcrop of the strata would not yield so copious a supply.

The water-bearing capacity of the formation has no doubt been increased by flexures which occur in the Ouse Valley north of Bedford, and water descends into the strata either directly or through the overlying porous Valley Gravels.

In Northamptonshire the Great Oolite is about 25 feet thick, a thickness continued into Lincolnshire, but there decreasing in places to 10 or 12 feet.

In these parts of the country, while yielding evidence of its permeability at the surface, it cannot be relied upon to yield much water at a great depth.

The **Fullonian** or **Fuller's Earth Formation** is mainly argillaceous, and extends from Dorset to Gloucestershire.

It consists of a thick mass of pale marl and clay, with occasional indurated bands and nodules, and with an intermediate division of Fuller's Earth Rock.

Economic Fuller's Earth occurs at Midford and Wel-low, near Bath. The rock is best developed in parts of Dorset and Somerset, at Thornford, Milborne Port, and Shepton Montague, where it is from 30 to 35 feet thick, and yields limited supplies of water. It is, however, too argillaceous to hold a large amount.

The total thickness of the formation on the Dorset coast is about 150 feet.

At Stowell, west of Templecombe in Somerset, as recorded by Mr. John Pringle from information given by Mr. W. Phelps, a thickness of 332 feet was proved in a boring, the total thickness in the neighbourhood being at least 340 feet. In the boring, the Upper Fuller's Earth Clay was 120 feet thick; the Fuller's Earth Rock, 35 feet; and the Lower Fuller's Earth Clay, 177 feet.¹ At Bath the total thickness of the formation is about 70 feet, and in Gloucestershire from 70 to 84 feet. Eastwards the beds diminish in thickness, and pass into the Upper Estuarine Series.

The **Upper Estuarine Series** in the Midland counties of England and in Lincolnshire consists of blue, purple, white, and variegated clays with sandy layers, bands of limestone with fossil oysters, lignite, and much mineral matter, such as pyrites, fibrous carbonate of lime ('beef'), concretions of the same material ('race'), and often nodules of iron-ore at the base. The thickness varies from 15 to 45 feet. The beds do not yield any serviceable amounts of water in the district above mentioned.

In Yorkshire the Upper Estuarine Series includes strata from beneath the Cornbrash to those known to

¹ Summary of Progress, *Geol. Survey* for 1908, 1909, p. 83.

be of the age of the Inferior Oolite, and it may in part represent the higher portions of that formation. It consists mainly of shales, with some bands of sandstone and ironstone, and includes a sandstone known as the 'Moor Grit' at the base. This Grit is the only water-bearing bed of consequence in the series. The total thickness of the series varies from about 10 to 220 feet.

The Inferior Oolite Series in England is divided as follows:

Southern and Western Counties.	Midland Counties and Lincolnshire.	Yorkshire.
Inferior Oolite.	Lincolnshire Limestone.	Middle and Lower Estuarine Series.
Midford Sands.	Northampton Beds { Lower Estuarine Series and Northampton Sand.	Dogger Series.

From Dorset to the northern end of the Cotteswold Hills the **Inferior Oolite** and **Midford Sands** are well developed. In the south, at Bridport and Yeovil the sands are thick and prominent, whereas the overlying limestones are much reduced in thickness, from a few feet to 45 feet. The united thickness is in many places about 200 feet.

The Sands contain more or less nodular bands of calcareous and shelly sandstone, the harder beds passing into a sandy and shelly limestone at Ham Hill, near Yeovil. At Bath the Sands are about 100 feet thick, and the overlying Oolite about 35 to 45 feet.

In the Cotteswold Hills north of Bath the Limestones gradually increase in thickness to 55 or 60 feet, while the Sands tend to decrease to 50 or 60 feet. In the neighbourhood of Stroud and Cheltenham the Sands are from 60 to 130 feet, decreasing northwards.

The Limestones, which at Stroud form a series about 160 feet thick, increase to 250 feet near Cheltenham. In the northern portion of the Cotteswold Hills local beds of clay as well as marl occur in the series.

From Dorset to the southern part of the Cotteswolds the water-supply of the Midford Sands and Inferior Oolite is practically united.

The Sands, however, are not persistent; they appear to be overlapped towards the Mendip Hills, at Doultling, near Shepton Mallet; while here and there they are absent in North Somerset, and again along the Cotteswold Hills in places north and north-east of Bath.

Near Doultling and Cranmore, where the strata have a south-easterly dip, much of the ground-water escapes along the scarp near Chesterblade, where the deep valleys contain strong springs.

The springs from the Inferior Oolite and Midford Sands of the Cotteswolds are as a rule more constant than those of the Great Oolite.

Near Bath there are springs from these strata, which yield upwards of 400,000 gallons a day. From the railway-tunnel east of Chipping Sodbury, in Gloucestershire, about 240,000 gallons per day were pumped. Farther north along the Cotteswold Hills, and especially from the neighbourhood of Stroud northwards, where a broader belt of Inferior Oolite is exposed, large supplies of water are gathered by the strata, and copious springs are met with. At Chalford, near Stroud, the

yield of the springs is estimated at from 6 to 9 million gallons per day.

In the Oolitic district of the Cotteswold Hills, the strata to be encountered in boring are indicated by the following record of a boring made, with the advice of the writer, by Mr. T. Holloway in 1892, on the northern side of Tetbury:¹

		Thickness.	Depth.
		Ft. in.	Ft. in.
Forest Marble	Oolitic shelly limestones	8 0	8 0
	Pale marly oolitic limestones	20 0	—
	Buff oolite	14 0	—
	Gritty marl	0 6	—
Great Oolite	Oolitic shelly limestones	7 6	—
	Oolite	84 0	—
	Grey earthy oolitic limestone	13 0	—
	Grey limestones	21 0	168 0
	Grey marl	8 0	—
Fuller's Earth or Fullonian	Grey limestone with <i>Ostrea</i>	1 0	—
	Hard grey marly bed	75 0	252 0
Inferior Oolite	Hard grey limestones	48 0	300 0

Water was tapped in a fissure of the Great Oolite at a depth of 147 feet, and it rose 28 feet, but the quantity was insufficient. (See p. 190.)

At the depth of 300 feet water was obtained from the Inferior Oolite at the rate of 2,964 gallons per hour, and after pumping for a fortnight the rest-level remained at the depth of 119 feet from the surface. The boring

¹ H. B. Woodward, 'Jurassic Rocks of Britain,' *Mém. Geol. Survey*, vol. iv., 1894, p. 508.

was lined with ordinary tubes to a depth of 250 feet, and with perforated tubes from 250 to 270 feet.

Evesham is supplied from springs that issue from the Inferior Oolite and Sands on the northern Cotteswolds; Gloucester is in part supplied from a reservoir at Witcombe.

Beyond the eastern Cotteswolds, at Chipping Norton, the beds are considerably modified, and we pass into the Midland type of the Inferior Oolite Series, with a base of Northampton Sand and overlying Lower Estuarine Series. For some distance the Lincolnshire Limestone is absent; it does not appear until we pass to the north-east of Towcester and reach Maidwell.

The **Lower Estuarine Series** consists of white and coloured sands and sand-rock, of black, purple, and green clays, and shales with lignite and ironstone nodules. It varies from 10 to 15 feet in thickness.

The underlying **Northampton Sand** consists of sands and sandstones more or less calcareous, the harder beds being sometimes fissile and serviceable for roofing, as at Duston and Collyweston. The lower beds become in places a valuable iron-ore, brown at the surface, and below-ground consisting of the grey carbonate of iron. The thickness of the beds varies from 5 to 30 feet. The Northampton Sand has yielded good supplies of water from wells and springs at or near the outcrop, but, as observed by Mr. Beeby Thompson, it has not furnished any considerable supplies at a depth, and when water has been obtained it is sometimes highly charged with sulphuretted hydrogen.

The **Lincolnshire Limestone** constitutes, where well developed, as in parts of Northamptonshire, and

especially in Lincolnshire, a grand water-bearing formation 80 to 100 feet thick. In Northamptonshire and some parts of southern Lincolnshire a good deal of Boulder-clay covers the formation, but elsewhere in Lincolnshire the formation is exposed over a wide belt of country comparatively free from Drift. Very copious supplies have been tapped along the dip-slope, beneath coverings of Great Oolite, Cornbrash, and Oxford Clay. Thus, near Bourne an artesian and overflowing supply of 5 million gallons a day was tapped in a boring.

Supplies obtained from this formation have been a great blessing to Peterborough, to many places in the Fenland, and elsewhere.

The well above mentioned was made for the Spalding waterworks at Bourne, in Lincolnshire, by Messrs. C. Isler and Co., in 1893-94; and the strata shown in the table on p. 199 were passed through with a shaft 6 feet deep, the rest by a boring of 13 inches diameter.

The chalybeate water found at depth of $65\frac{1}{2}$ feet was shut out. The main springs were tapped at $78\frac{1}{2}$ feet, the water then rising very slowly, and taking twenty-four hours to overflow. Deeper, the volume increased rapidly, and the overflow was 1,872,000 gallons a day at the depth of 100 feet, 2,592,000 at 120 feet, and more than 5 million gallons at 134 feet. The water rose 34 feet above the ground, the level of which was about 78 feet above Ordnance Datum.¹

Reservoirs in the upland valleys, where Northampton Sands are based on Upper Lias Clay, have been constructed between Teeton and Ravensthorpe for the

¹ H. B. Woodward, 'Water-Supply of Lincolnshire,' *Mem. Geol. Survey*, 1904, p. 67.

Boring at Bourne.				Thickness.	Depth.
				Ft. in.	Ft. in.
Made Ground	...	...	...	2 0	—
Drift	...	{ Clay	...	1 6	—
		{ Gravel	...	1 0	4 6
Kellaways		{ Clay	...	2 0	—
Beds		{ Loamy clay	...	1 0	7 6
Cornbrash	...	{ Rock and shells	...	2 0	—
		{ Limestone	...	6 6	16 0
Great Oolite Clay		{ Hard blue clay	...	4 0	—
		{ Mottled clay	...	10 0	—
		{ Shaly clay, dark blue and green	...	1 0	—
		{ Hard blue rock	...	2 0	—
		{ Dark blue soft rock with shells	...	1 0	—
		{ Hard blue clay	...	2 0	36 0
Great Oolite Limestone		{ Hard blue limestones	...	11 0	—
		{ Harder limestone, dark green	...	1 0	48 0
		{ Dark green clay	...	7 0	—
		{ Hard blue rock	...	1 0	—
Upper Estu- arine Series		{ Dark and light green clay	...	9 0	—
		{ Hard rock (with cha- lybeate water)	...	0 10	—
		{ Light green sandy clay	...	9 8	—
		{ Black clay and lignite	...	0 6	76 0
Lincolnshire Limestone		{ Grey porous rock (oolitic limestone)	...	1 6	—
		{ Hard oolitic limestone	...	33 0	—
		{ Very hard rock	...	5 6	—
		{ Hard limestone	...	5 6	—
		{ Hard oolitic limestone	...	12 6	134 0

supply of Northampton, and near Sywell for Rushden and Higham Ferrers.

In Yorkshire the **Lower and Middle Estuarine Series** comprise a great series of shales and sandstones, with thin coal-seams, ironstone bands, and bands of limestone. The beds are very irregular, and the water-bearing sandstones are inconstant. The combined series attains a thickness of from about 80 to 480 feet, and the underlying **Dogger Series** from 10 to a little over 100 feet. The lower portion of the Dogger consists of grey and yellow sands, and the upper part of a nodular calcareous and ferruginous rock. Strangways has remarked that the largest amount of water is probably held in these basement-beds above the Upper Lias. In the Estuarine Beds the supplies of water are local.

Sandstones of the age of the Inferior Oolite occur in Skye and Raasay, and are capable of yielding considerable amounts of water. In those regions, however, springs and burns rarely cease to flow, and they are mostly depended on for purposes of water-supply.

LIAS.

The **Upper Lias** is in the main a great impervious series of dark shales or clays with nodules of limestone, with, at the base, several bands of limestone alternating with clays.

In Dorset and Somerset the formation is less prominent than in other counties. Near Bridport it is largely formed of sandy shales, with a thin rock layer at the base, altogether about 70 feet thick. This basement-bed is more important near Yeovil, where it consists of from 4 to 6 feet of pale-limestones, resting on the rock-bed at the top of the Middle Lias (there about 18 inches thick), as it has yielded supplies of

water to many cottages. In Somerset the Upper Lias is 40 or 50 feet thick; in Gloucestershire it has been reckoned to be from 70 to 150 feet; in North Gloucestershire its thickness was proved to be about 120 feet; in Oxfordshire it is from 16 to 80 feet or more; in Bedfordshire, 60 or 70 feet; in Northamptonshire, from 85 feet near Peterborough to more than 200 feet in the northern part of the county; in Lincolnshire, from 120 feet at Grantham to 80 feet at Lincoln, and 25 feet farther north; in Yorkshire, about 210 feet.

Its importance from the point of view of water-supply lies mostly in the fact that it supports water in overlying permeable strata, and throws out springs.

The **Middle Lias** is locally an important water-bearing formation, but the strata are very inconstant. In general it comprises the following subdivisions:

Marlstone or Rock-Bed.—Ferruginous iron-shot limestone, from 1 foot to 12 feet thick, in Dorset and Somerset; passing in Oxfordshire into rich beds of iron-ore, 15 to 30 feet thick; again changing into a ferruginous freestone, 30 feet thick, at Edge Hill. Farther north-east it is an important iron-ore in parts of Northamptonshire, Leicestershire, and Lincolnshire, of variable character, 12 to 25 feet thick, but sometimes reduced to one or two thin layers with no water-bearing capacity, and sometimes absent or replaced by clays.

Sands and Shales.—Underlying the Marlstone there are laminated micaceous sands and shales, and sometimes beds, 40 to 60 feet thick, of sand and concretionary masses of sandstone that are water-bearing, as in Somerset, at Glastonbury and Pennard Hill; and on the Dorset coast, near Bridport.

The lower portion consists of impervious shales and clays, with occasional hard bands and nodules.

The lower division, beneath the Marlstone, is more than 340 feet thick in Dorset, about 230 feet in Somerset, 150 in Gloucester, 40 in Oxfordshire, about 90 in Northamptonshire, from 40 to 80 in Lincolnshire, and about 100 feet in Yorkshire.

The beds pass downwards into the clays of the Lower Lias.

As a water-bearing formation, the Middle Lias is very uncertain, and in many places waters are more or less ferruginous.

Much water has been obtained from the Middle Lias in Northamptonshire. Thus, in 1836, near Northampton, an amount equal to 800,000 gallons per day was tapped in a boring for coal. In 1846 another boring was made to obtain the water for the town, and 500,000 gallons per day was obtained. The quantity, however, diminished; in 1871 only about 280,000 gallons could be supplied, and the supply continued to decrease owing to the fact that in this and other wells the water was taken from the formation more rapidly than it could be replenished from natural sources. (See p. 78.)

Mr. Beeby Thompson has observed that in this county five distinct horizons in the Middle Lias have yielded water, although not at any one locality, the water being derived from hard bands of rock. The Marlstone is, however, the most important source. Efforts to get water from it to the south and east of the River Nene at Wellingborough have not proved successful.¹

In Yorkshire the sandy beds of the Middle Lias

¹ See 'Water-Supply of Bedfordshire and Northamptonshire,' *Mem. Geol. Survey*, by H. B. Woodward and B. Thompson, 1909.

yield local supplies of water, in some cases from 1,000 to 3,000 gallons a minute being obtained from wells, as noted by Strangways.

The **Lower Lias** consists generally of a mass of clays and shales with occasional bands and nodules of limestone, from 300 to 600 feet or more thick, overlying a mass of limestones that alternate with shales, from 20 to about 200 feet thick. The greatest recorded thickness of the Lower Lias is at Mickleton in Gloucestershire, 961 feet.

The limestone division is water-bearing, especially at or near the outcrop, where the beds are more jointed and fissured, and permanent springs are met with; but the supplies are never great, though sufficient for a cottage or small house may be drawn from a well. Rarely, as much as 5,000 gallons a day has been obtained. As the soil is tenacious clay with included blocks of weathered limestone, and in dry weather the ground is much fissured, impurities may find their way in some cases through the cracks into the water-bearing strata.

At a depth the bands of shale and clay that occur every foot or two, as a rule, prevent the circulation of water; so that deep wells are never to be recommended.

On the borders of the Mendip Hills there is locally, as near Shepton Mallet, a mass of limestones with little or no shale; but a well sunk 80 feet in the Lias obtained no water, probably because the strata rest on and abut against the fissured Carboniferous Limestone, and water is carried away through that formation.

At Lyme Regis, Watchet, Street, Keinton Mandeville, Bridgend, Harbury, Rugby, Stratford-on-Avon, and in some parts of Leicestershire, Nottinghamshire, and Lincolnshire, the stone-beds are well developed, and

local wells may be successful. In Yorkshire the limestone bands are far less prominent, and no supplies are to be expected.

NEW RED SANDSTONE SERIES: TRIASSIC AND PERMIAN.

The New Red Sandstone Series consists of two groups known as the Trias and Permian, and these are made up for the most part of red and variegated marls and sandstones, together with local beds of breccia and conglomerate. The Permian includes also the important beds of Magnesian Limestone, developed in Nottinghamshire, Derbyshire, Yorkshire, Durham, and Northumberland.

The Rhætic Beds, which form a connecting link (Passage-beds) between the Lower Lias and Keuper Marls, are persistent wherever opportunity has been afforded of proving their occurrence; but they have not been recognized in Cumberland, and have been rarely exposed in Yorkshire.

The New Red rocks rest everywhere in this country on an irregular and eroded surface of the older rocks. They fill up inequalities and overlap lower subdivisions; there is evidence of local and contemporaneous erosion, so that the thickness of the different members is subject to much variation. On these accounts estimates of the depth at which water-bearing rocks are likely to be reached beneath coverings of Red Marls are more or less speculative. (See G in Fig. 5.)

The following table gives estimated thicknesses (in feet) of local subdivisions in the New Red Sandstone Series beneath the Rhætic Beds:

	South-Western England.	Midland.	Cheshire and Lancashire.	Lake District.	North-Eastern Counties.
Keuper and Bunter	Upper Marls, 1,000 to 1,350 Upper Sand- stones, 200 to 530 Conglomerates and Pebble Beds, 70 to 100	Red Marls, 600 to 3,000 Waterstones and Basement Beds, 150 to 450 Upper Mottled Sandstone, Pebble Beds, and Lower Mottled Sand- stone, 250 to 1,250	Red Marls, 2,000 to 3,000 Waterstones, Sandstones, and Basement Beds, 400 Upper Mottled Sandstone, 500 to 800 Pebble Beds, 1,000 and more Lower Mottled Sandstone, 400 to 500	Red Marls, 30 to 50 Kirklington Sand- stone, 170 to 400 Upper Gypseous Shales, up to 700 St. Bees Sand- stone, 500 to 2,000	Red Marls and Sand- stones, 1,640
Permian.	Lower Marls with Sand- stone, 120 to 850 Lower Sand- stones and Breccias, 500 to 1,500	Marls and Sand- stone, Mag- nesian Lime- stone Series, 80 to 500.	Magnesian Marl, 100 Limestone, 10	Lower Gypseous Shales, with local Mag- nesian Lime- stone, 350 to 500 Penrith Sand- stone and Brec- cia (Brockram), 500 to 1,000	Magnesian Limestone Series, 500 to 600

TRIAS.

The **Rhætic Beds** consist of a series of white limestones and marls (White Lias), black shales, and grey marls, from about 30 to 100 feet in thickness, and sometimes more.

In parts of Somerset and Dorset, where the upper subdivision of White Lias is developed to the extent of 20 or 30 feet, limited supplies of water are yielded to wells. If sunk into the underlying Black Shales, the waters are liable to be charged with sulphuretted hydrogen. In a well sunk at Penarth in 1892, for the Cement and Lime Works, water was obtained at the base of the Grey Marls, which occur below the Shales and above the Red Marls, the quantity, as recorded by De Rance, being about 2,000 gallons an hour, and the depth, where reached, about 77 feet.

The Red rocks of the Trias, which lie beneath the Rhætic Beds, comprise a great series of variegated marls, sandstones, conglomerates, and pebble-beds.

The **Upper or Keuper Marls** comprise a great thickness of red and variegated marls and clays with subordinate beds of sandstone. In mass they constitute an impervious formation. Locally they contain important beds of rock-salt and gypsum or alabaster.

In the Bristol district, along the borders of the Mendip Hills, and in southern Glamorganshire, the Keuper Marls pass into sandstones and conglomerates along the original borders of the areas in which they were accumulated. As a rule there is also conglomerate at the base of the formation. This is generally known as the Dolomitic Conglomerate.

Considerable accumulations of water are met with in the joints and fissures of this rock.

A well at the Ely Paper Mills, Cardiff, of which a record was published by De Rance, was carried to a depth of 244 feet through superficial deposits, Red and Green Keuper Marls, into underlying beds of 'rock,' and yielded a supply of 12,000 gallons per hour.

The bands of sandstone intercalated in the Red Marls, sometimes known as Upper Keuper Sandstone, are not very constant, but they yield small amounts of water. They occur in the Vale of Taunton in Somerset, in Gloucestershire, Worcestershire, and Warwickshire. In Leicestershire the bands of sandstone, which alternate with marl in rapid succession, are known as 'skerries.'

Wells sunk in the Keuper Marls therefore sometimes obtain limited supplies of water from the local intercalations of sandstone.

Lower Keuper Sandstone.—At the base of the Keuper Marls there is a division sometimes termed the Waterstones: not because they are water-bearing; the name was originally applied by G. W. Ormerod, from the fact that they resembled watered silk—a wavelike pattern produced by sprinkling water on the surface and pressing the silk with rollers. The Waterstones sometimes yield good building-stone; sometimes they comprise irregular alternations of marl or shale and soft sandstone. Below them come the Keuper Basement Beds, which consist of sandstones (locally grouped as Frodsham Beds in Cheshire), marly beds, and conglomerate or breccia.

In mass the strata may yield a good deal of water, and Strangways has noted that a supply of 390,000

gallons a day was obtained from the formation at Ellistown in Leicestershire.

Bunter.—The series underlying the Keuper division of New Red Rocks is exceeding variable in character, and from a water-bearing point of view no particular or persistent plane of division can be made between the sandstones classed as Lower Keuper and those grouped as Bunter.

They comprise a series of mottled or variegated sandstones and pebble-beds in the Northern and Midland counties; and in Devonshire and Somerset a mass of sandstones (partly of the age of the Keuper Sandstone) underlaid by the Budleigh Salterton pebble-bed, and by massive conglomerates in West Somerset. The pebble-bed in Devonshire is loose and water-bearing; the conglomerates as a rule are hard, and water is only yielded from joints and fissures.

The mottled sandstones and pebble-beds of the Bunter have yielded large supplies of water in the Midland and North-western counties, from springs, wells with headings, and borings. The formation, though sometimes capable of subdivision into Upper and Lower mottled sandstone with intervening pebble-beds, is not to be separated in many parts. It constitutes one set of strata, the next in importance to the Chalk, among the water-bearing formations of England. The sands and soft sandstones hold much water, on account of their fairly uniform rounded grains, the term 'millet-seed grain' having been applied to the sand grains composing the strata in many places. It was estimated by De Rance (1896) that $\frac{1}{3}$ of the rainfall could be pumped from the formation. Water is thus yielded freely from the mass of the strata, also from

faults; less commonly from fissures than in many other formations. The beds are less subject than the Chalk to great fluctuations in the water-table, but De Rance (1892) noted that the cone of exhaustion in the Liverpool district extended across an area of about six miles.

Where exposed at the surface the strata are liable to receive pollution, but the sands furnish a good natural filter-bed.

G. H. Morton published records of twelve public wells that were situated within four miles of Liverpool Town Hall, the united average daily yield of which amounted to 12,703,770 gallons. (See p. 119.) He mentioned also that nearly 20 million gallons were pumped daily from the Mersey Tunnel, principally from the Birkenhead side; but analysis shows that about half the amount was derived from the river, on account of the saline ingredients in the water.¹

The water from the Bunter Sandstone generally is hard (9° to 15°), and it has been remarked that the hardness increases with the age of the wells. (See p. 265.)

Beneath Alluvial and Glacial Drift at Widnes and Warrington, the water in the Sandstone series is pent up, and when tapped rises to the surface under artesian conditions.

Waters too highly impregnated with sodium chloride or calcium sulphate have been encountered in several deep borings carried through the New Red Marl. Thus, at Rugby a well which was commenced in Glacial Drift and Lower Lias was carried down to the Keuper Waterstones, when saline water was encountered at a

¹ 'Geology of the Country around Liverpool,' 2nd edit., 1891, p. 179.

depth of 1,145 feet. At Lincoln a somewhat similar boring was carried through Lower Lias to the Bunter Sandstone, which was reached at a depth of 1,563 feet. In this case also the water was too saline for the supply of the city. On the other hand, a boring at Stratford-on-Avon, of which particulars were published by Dr. Horace T. Brown,¹ was carried through Keuper Marls, with much gypsum, to a depth of 804 feet, passing into sandstones at a depth of 604 feet. Above the sandstones the strata were quite dry, but directly they were reached water was met with, and ultimately a supply of 8,000 gallons an hour was obtained by pumping. The artesian head of water, as noted by Dr. Brown, was considerable, and 'sufficient to afford a natural flow of 1,800 gallons per hour at a height of 50 feet from the surface.' The water contained only 21 grains per gallon of mineral matter, including $4\frac{1}{2}$ of sodium chloride, and no calcium sulphate.

The St. Bees Sandstone and the Penrith Sandstone yield good supplies of water; the former, it is considered, is somewhat the closer in texture, and water passes less freely through it.

The **Magnesian Limestone** consists in part of dolomite or true magnesian limestone, in part of ordinary limestone, and sometimes, as at Mansfield, of dolomitic sandstone or sandy dolomite. The beds, often open in texture, yield considerable amounts of water, most of which is very hard, but some may be only impregnated with calcium carbonate.

The Magnesian Limestone series includes also beds of marl, sandstone, and sometimes breccia, so that

¹ *Geol. Mag.*, 1896, p. 55.

locally there are two or three subdivisions of Magnesian Limestone. At the base there are, in Yorkshire and Durham, beds of sand (quicksand), about 20 feet thick.

In Nottinghamshire the marls and sandstones above the Magnesian Limestone are considered by Mr. R. L. Sherlock to be intimately linked with the Bunter Beds.

Among towns supplied with water from the New Red Sandstone series (Permian and Trias) are Teignmouth (in part), Gloucester (in part from well at Newnham, 170 feet deep, water hard), Malvern (in part), Kidderminster, Stourbridge, Warwick, Tamworth, Nuneaton, Lichfield, Nottingham, Worksop, Gainsborough, Warrington, Hoyle, etc. Lincoln, as I am informed by Mr. H. Preston, is to be supplied from borings in the Bunter Sandstone at Elkesley, near Retford.

Manchester and Birmingham, as well as Liverpool, were at one time mainly supplied from wells in the New Red Sandstone. At Birmingham as much as 3 million gallons of water was obtained from each of three wells, and single wells at Nottingham and Wolverhampton have yielded a like amount.

CHAPTER XI

THE WATER-BEARING STRATA OF BRITAIN (*Continued*)

UPPER PALÆOZOIC ROCKS.

IN dealing with the formations older than the New Red Sandstone Series (Permian and Trias), there is no occasion to enter into so much detail as with the Secondary and Tertiary formations.

The conditions affecting supplies of water in the British Isles are somewhat different in the Palæozoic rocks from those in the more regularly disposed newer strata. The older rocks as a rule are harder and far less permeable in mass; they have been much more folded and disturbed, and, although supplies of water are freely obtained from joints and fissures in many of the formations, the most important supplies are obtained from springs, streams, and reservoirs, rather than from wells and borings. Shallow wells, however, are not uncommon.

CARBONIFEROUS.

The **Coal Measures** consist of a great thickness of shales and sandstones, with occasional thin limestones, seams of coal, and bands of ironstone. The thicker beds of sandstone are water-bearing and may yield good supplies; but the beds are often lenticular or

Upper Palaeozoic Rocks of Glamorgan and Monmouth.		Ammanford, Swansea, and Gower.	Merthyr Tydfil, Pontypridd, and Bridgend.	Abergavenny, Newport, and Cardiff.
Coal Measures	Upper Coal Series: Shales and sandstones, few coal-seams	Feet. 1,050	Feet. 230	Feet. 300
	Pennant Grit: Massive grits, with sandstones and shales, some coal-seams	2,850	1,800 to 2,800	800 to 980
	Lower Coal Series: Mainly shales, with ironstones and coal-seams	900 to 3,075	2,700.	850 to 1,600
Millstone Grit: Pebbly grit, shales, and sandstones ...		1,300 (on north); 800 (mostly shale on south)	350 (on north); 1,500 (on south)	200 to 450 (on south)
Carboniferous Limestone Series	Upper Limestone Shales ...	10 (on north); 800 (on south)	20	—
	Main Limestone ...	700 to 3,000	430 to 1,600 (on south)	150 and less to 800
	Lower Limestone Shales ...	30 to 500	70 to 300 (on south)	150 and less to 300
Old Red Sandstone	Red and yellow sandstones, grey grits, and conglomerates	30 (on north) to 320	200	120 to 200
	Brownstones: Sandstones* and grits, with some marls	400 to 1,600	1,400 to 1,500	500
Senni Beds and Red and Mottled Marls: Red and green sandstones, marls and shales, occasional conglomerate, and cornstones		About 5,000, but very thin in Gower	1,000 or more	2,800

wedge-shaped, and supplies are thereby limited. The water in many cases is not of very good quality, and is sometimes very saline. (See p. 299.) Wells in Coal districts are liable to be affected by subsidences due to underground workings.

In the Bristol and Somerset, Forest of Dean, and South Wales Coal-fields, the Coal-measures contain an intermediate division of great thickness known as the Pennant Grit. Copious springs issue from the strata, and have been utilized in many places for village supplies.

Much water was encountered in the Pennant Grit during the construction of the Severn Tunnel, and since the completion of the works about 20 million gallons of water have had to be pumped daily from the tunnel, a part issuing from other strata.

In the Culm-measures of Devon and Cornwall, the beds, which consist mainly of sandstones and shales, are so fractured and contorted that it would be difficult to recommend any particular site or predict the depth at which an abundant supply would be found. In most localities water would occur in the fissures of the shattered strata.

In South Wales the subdivisions of the Carboniferous Rocks and Old Red Sandstone have been worked out in detail by the Geological Survey, under the personal superintendence of Dr. A. Strahan. The table on p. 213 shows the varying thicknesses of the strata.

In North Wales (Flintshire) the Carboniferous Rocks have been divided by G. H. Morton as follows:¹

¹ 'Appendix to Geology of the Country around Liverpool,' 1897.

				Feet.
Coal-measures	{	Middle Measures ...	...	700
		Lower Measures ...	...	300
Cefn-y-Fedw Sandstone	{	Gwespyr Shale ...	...	150
		Gwespyr Sandstone ...	...	120
		Holywell Shale ...	...	100
		Cherty Sandstone ...	...	250
Carboniferous Limestone	{	Upper Black Limestone ...	...	200
		Upper Grey Limestone ...	...	500
		Middle White Limestone ...	...	600
		Lower Brown Limestone ...	...	400
		Red Basement Beds...	...	3

These particulars may be taken as a sample of the changes which occur in different districts.

The variability in the character and thicknesses of each formation has a most important bearing on questions of water-supply, and when reservoir-sites are under consideration it is necessary to study the local details published on the maps and sections, and in the memoirs of the Geological Survey, and in other works, and to verify the facts on the ground.

The **Millstone Grit** is a great series of hard and close-grained or pebbly grits, sandstones, and shales, ranging in thickness from about 200 to as much as 3,000 feet.

A. H. Green¹ remarked that throughout South Lancashire, North Staffordshire, Derbyshire, and the southern part of Yorkshire, the Millstone Grit closely conformed to the series summarized as follows :

		Thickness in Feet.
<i>Rough Rock or First Grit</i> : Coarse felspathic grit, often with flagstone at base ...	...	50 to 200
Shales (impersistent) ...	...	—

¹ See Green, 'Geology of the Yorkshire Coal-field,' *Mem. Geol. Survey*, 1878, pp. 27, 28.

	Thickness in Feet.
<i>Second Grit</i> : Fine-grained sandstones and shales	60 to 100
Shales	75 to 150
<i>Third Grit</i> : Coarse gritstone, flaggy at base, and often with seam of coal on top ...	200 to 300
Shales	300 to 500
<i>Kinder Scout or Fourth Grit</i> : Coarse massive grits, often conglomeratic (with quartz pebbles), and with occasional flagstone ...	Up to 500

These subdivisions are as a rule well defined in Derbyshire, but in proceeding northward, beyond the extreme south of Yorkshire, the Millstone Grit was found by Green to be much more largely developed and far more variable; and he adopted the following general divisions for the Millstone Grit of the Yorkshire Coal-field:

	Feet.
Rough Rock or Topmost Grit	75 to 100
Shales	125 to 240
Middle Grits: Sandstones, gritstones, and shales; variable as regards the sandy beds in number, character, and thickness ...	600 to 1,000
Shales	About 260
Kinder Scout or Lowest Grits, with shales ...	550 to 1,400

The thicknesses here given must be taken as subject to much local modification.

Subsequent researches in Derbyshire, Cheshire, and Staffordshire, show that it is desirable to abandon the use of such terms as first, second, and third grits, and to group the series as above noted. Local names are applied to particular bands of grit, as the Chatsworth or Belper Grit, in the Middle Grit Group.¹

¹ See C. B. Wedd, Summary of Progress, *Geol. Survey* for 1908, 1909, p. 13.

The grit-bands yield many copious springs, and a good deal of water has been obtained from them by shafts and borings. More often water, when required in large quantities, is derived from impounding reservoirs in the moorland valleys.

Congleton, Leeds, Bradford, Halifax, Keighley, Ilkley, Harrogate, Wrexham and other towns, are thus supplied.

For the supply of Harrogate, Knaresborough, and certain villages, as noted by Strangways, there are storage reservoirs with a united capacity of nearly 1,000 million gallons, the water in which is derived from watershed areas extending over 5,770 acres and having a mean annual rainfall of 30 inches. Further works are being undertaken.

In Scotland a series of sandstones and grits with some bands of limestone, clays, and coal-seams, the whole known as the Moor Grit, is grouped with the Millstone Grit. It is about 700 feet thick in parts of Fifeshire.

The **Yoredale Rocks**, owing to the intercalation of limestones with shales, sandstones, flagstones, and grits, yield harder water. They comprise a series that replaces the upper beds of the Carboniferous Limestone Series of the West of England, and the strata, named from their development in Yoredale or Wensleydale in Yorkshire, extend from Derbyshire into the Northern counties, and attain thicknesses of 2,000 to 4,500 feet.

The name Pendleside Group has been applied in Lancashire and other parts of the country to the shales and limestones that occur between the main mass of Carboniferous Limestone and the Millstone Grit. They are the Upper Limestone Shales of some geologists, the Yoredale Rocks of others; but the fossils of the strata of Pendle Hill, Lancashire, as shown by Dr.

Wheelton Hind and Mr. J. Allen Howe, indicate a later stage than those of the true Yoredale Rocks of Wensleydale. At Pendle Hill the thickness of the Pendleside Group is estimated at 1,500 feet, and consists mainly of shales with an included mass of limestones (the Pendleside Limestone). The limestones are but locally well developed.

Below the Millstone Grit at Harrogate is a series of shales, cherty limestones, and grits, termed by Strangways the Harrogate Roadstone Series, which probably belongs to the Pendleside Group. Some of the shales contain a good deal of pyrites, the decomposition of which has given rise to the celebrated sulphur waters of Harrogate. The springs rise from a faulted anticline.

As an example of the true Yoredale Rocks, the following table, published by the Geological Survey, shows the varying thickness of the strata in West Yorkshire:¹

					Feet.
Yoredale Rocks	{	Cherty beds, sandstone, and shale ;			
		variable	...	...	0 to 90
		Main Limestone	...	...	50 to 100
		Sandstone and shale	...	...	70 to 100
		Underset Limestone (thins away south)			
		...	...	...	0 to 80
		Sandstone and shale with two thin			
		limestones	...	...	100 to 345
		Middle Limestone	...	...	15 to 110
		Sandstone and shale	...	...	30 to 150
		Simonstone Limestone	...	...	15 to 60
		Sandstone and shale	...	...	30 to 180
		Hardraw Scar Limestone (some- times in two divisions)			
		...	...	...	25 to 80
		Sandstone and shale thinning out south-eastward			
		...	...	...	0 to 140

¹ 'Geology of the Country around Ingleborough, with Parts of Wensleydale and Wharfedale,' *Mem. Geol. Survey*, by J. R. Dakyns and others, 1890.

The **Carboniferous Limestone**, known also as the Mountain Limestone, consists for the most part, in the Western and Midland counties of England, in South Wales, and in Ireland, of a mass of hard, well-bedded limestones with occasional nodules and bands of chert. Locally it is more or less subdivided by shales.

Acted upon by carbonated water, or water holding carbonic acid in solution, it has everywhere at the surface, and to a considerable depth underground, been furrowed or eroded into caverns of various dimensions.

The cracks and joints have been enlarged into wide irregular fissures, known as 'grikes' or 'gilles,' in western Yorkshire and Westmorland. These great tracts of bare limestone, which form the plateaux, are known as 'helks' or 'clints.' The rock itself is compact and dense and practically impervious, yet no formation allows the rainfall more readily to penetrate underground. On this account there is considerable liability to pollution, and the formation has not very extensively been used as a source of water-supply.

If the rock be dense and there be an absence of fissures or caverns, the strata may hold up water at various levels; otherwise, if the limestone extend to below the level of adjacent streams, the water in caverns may indicate the plane of saturation.

The springs at Wells in Somerset, and the streams of Wookey and Cheddar, are derived from the Carboniferous Limestone of Mendip and in part from the rainfall on the Old Red Sandstone, which, flowing across the outcrop of the Lower Limestone Shales, enters the swallow-holes on the tableland of the Carboniferous Limestone. (See Fig. 16.) The water is given out where the Keuper Marls abut against the

lower slopes of the hills. Oystermouth, Bridgend, Clevedon, Weston-super-Mare, and Frome, derive their supplies of water from the Carboniferous Limestone, in the former three cases from springs, and in the latter two from wells. In Northumberland, as at Bamburgh, in Derbyshire, and other parts of the North of England water is obtained from shallow wells in the limestone-series.

In Northumberland and in Scotland the Carboniferous Limestone Series includes in the upper part many bands of sandstone and shale, with seams of coal and ironstone as well as layers of limestone; while the lower part, grouped as the Tuedian and Calciferous Sandstone, is somewhat similarly constituted, and contains also bands of cement-stone.

DEVONIAN AND OLD RED SANDSTONE.

The **Old Red Sandstone** is a composite formation of sandstone, conglomerate, and marl, with occasional beds of concretionary limestone or cornstone. The upper portion, in the West of England and Wales, consists for the most part of sandstones with conglomerate; the lower portion, of marls and sandstones with bands of cornstone. The upper beds naturally hold and yield more water. As a rule the sandstone is too hard and dense to yield free supplies of water except from joints and fissures. There are, however, softer beds near Malvern and Hereford, and in Monmouthshire, which have yielded good supplies from wells. Chepstow is supplied by springs and borings.

In Monmouthshire and South Wales supplies are obtained from springs and gathering grounds in the

upland regions of Old Red Sandstone, for Monmouth, Newport, Brecknock, Merthyr Tydfil, and Cardiff.

The conglomerates, where disintegrated at the surface so as to form a loose gravel, yield springs along the Mendip Hills, notably along the uplands north of East and West Cranmore. Wells in Somerset is supplied from a spring at Hole's Ash, near Milton, that comes from the Old Red Sandstone. In Scotland the higher beds of Old Red Sandstone include the red and yellow sandstones of Fifeshire, Elgin, Nairn, and Orkney; at a lower horizon come the flagstones of Caithness, red sandstones and conglomerates; while the lowest beds in the district of Lorne comprise sandstones and volcanic rocks with masses of boulder-conglomerate.

Devonian Rocks in this country are practically confined to Devon, Cornwall, and western Somerset.

They consist of shales and slates, hard sandstones, quartzites, and limestones. In North Cornwall, North Devon, and West Somerset, the limestone-bands are thin and impersistent. Those of any importance as water-bearing strata are to be found only in South Devon and the Cornish borders, near Newton Abbot, Torquay, and Plymouth. Like the Carboniferous Limestone, these beds yield water in fissures, and are equally liable to surface pollution. The water is moderately hard, while that thrown off from the other strata is naturally soft.

The sandstones and quartzites are too dense to yield water except in joints and fissures and in the shattered portions near the surface. Minehead is supplied from springs in the adjacent hills; Bridgewater, from the Quantock Hills. Water is also yielded by the joints and shattered surfaces of the slates and shales known as

'killas' in Cornwall and as 'shillet' or 'shellat' in Devon; but supplies are much diminished in dry weather. From such sources Ilfracombe, Dartmouth, Truro, and Hayle, are supplied by springs and reservoirs.

There are many shallow wells in the jointed and fractured slaty rocks of Cornwall and Devon, and it has been observed that wells on the higher grounds are most liable to run dry in summer.

Mr. J. B. Hill has noted that the water-supply of St. Agnes and Mount Hawke is obtained from the adit of an old mine,¹ and Redruth is in part supplied from a similar source. Underground waters from metaliferous mines are, however, in some cases poisonous. (See p. 285.)

Mines worked below sea-level, and sometimes beneath the sea, are liable to influxes of saline and sometimes thermal water. (See p. 301.)

LOWER PALÆOZOIC.

The **Silurian**, **Ordovician**, and **Cambrian** rocks, which consist very largely of shales and mudstones, sandstones, slates, and grits, and some limestones, such as those of Aymestry, Wenlock, Woolhope, and Bala, form hilly and mountainous country, with many springs; nevertheless, much of the rainfall is drained superficially off the surface, unless stored up in peaty accumulations. The water is mostly soft, except where it issues from the limestone strata, but the hardness usually does not exceed 10.°

In the Isle of Man springs and streams from the mountain region supply soft water for Douglas and

¹ 'Geology of Falmouth,' 1906, p. 112.

other places. Keswick is supplied from similar sources on Skiddaw, and Church Stretton from the Longmynd. Droitwich obtains a supply from springs on the Lickey Hills, and Criccieth from an old slate-quarry.

Supplies from these older rocks are as a rule best obtained by impounding reservoirs.

ARCHÆAN AND IGNEOUS.

Various igneous, metamorphic, and crystalline rocks yield supplies of water from joints, shattered and decomposed masses, and veins.

Where the New Red Marls abut against the old crystalline rocks on the eastern side of the Malvern range, springs are given out from fissures and decomposed rock, and sometimes they issue from fringes of the New Red Sandstone beneath the Marls. On this eastern side the wells at Malvern are noted. (See p. 85.)

On the western side of the range springs issue from the Silurian limestones, and yield rather hard water.¹

Among great sheets of basalt with intruded sills, the decomposed portions are water-bearing, and give rise to springs, as in the Western Isles or Inner Hebrides.

In South Wales, north of Haverfordwest, considerable springs issue from the decomposed igneous rocks, and many other instances might be given.

Lacustrine beds of white clay with sands and pebbly layers and volcanic débris, intercalated with sheets of lava, yield water in the Snake River plains of Idaho, as noted by Mr. I. C. Russell (1892).

Granite is an important water-yielding formation. It affords supplies from springs which issue from joints

¹ J. Phillips, *Mem. Geol. Survey*, ii., part 1, 1848, p. 16.

or clefts in the rock, and also from springs and wells in the disintegrated surface portions. Decomposed elvan dykes also yield water.

Where a boss of granite is surrounded by slaty rocks on lower ground, springs are given out along the margin, and from such sources Falmouth, Penryn, Redruth (in part), Camborne, and Bodmin, are supplied. St. Austell obtains water from a disused China-clay pit. Dartmoor has yielded supplies for Paignton, Newton Abbot, and Torquay.

In the Channel Islands the granitic rocks are decomposed to a depth of 20 or 30 feet, and permanent springs issue at the junction with the solid and practically impervious granite below. There is also a good deal of seepage along the lower grounds in Jersey. (See pp. 140, 260.)

CHAPTER XII

ON PROSPECTING FOR WATER

REPORTS on the prospects of obtaining supplies of water have also to take into account any possible sources of contamination that may affect the gathering ground and the water-bearing strata. The methods of proceeding will differ according to the requirements and the district or country. Much depends on whether the geological structure and physical features are well known, or partially known, or practically unknown, and whether water is to be obtained above or below ground.

With River-water no geological advice as a rule is needed ; the questions are those of quantity and quality, of filtration and pumping, of reservoirs and compensation. So also with Rain-water, which may be regarded as a last resort in the matter of water-supply.

In the case of rivers it is of course important to note the general character of the strata in the catchment area, as the flow is more constant where there are considerable tracts of permeable rocks which throw out springs, than where the rocks are mostly dense and impervious.

The questions with which we are concerned are those relating to—

1. Deep-seated springs or well-waters.
2. Upland surface-waters, impounded.
3. Shallow springs or well-waters.

Where more than one good source may be found, the question of well or boring, or of supply by gravitation from spring or reservoir, is a matter to be dealt with by the Engineer.

In regions where little or no geological information is available, all local evidence with regard to rainfall, the permanency of flow of springs, streams, and rivers, must be gathered; traverses must be made to ascertain the general nature, arrangement, and thicknesses, of the formations, in cliffs and river gorges, so that as far as possible the sources of springs may be ascertained.

Sands and gravels, most sandstones and limestones, may be expected to yield water in appropriate situations. In the case of sands and sandstones, the character of the water depends upon whether they are calcareous, purely siliceous, or ferruginous, when the water may be hard, soft, or chalybeate.

With reference to most parts of the British Islands, excepting the northern portions of Scotland, geological maps on the scale of one inch to a mile have been published. For many parts of Great Britain (excepting northern and central Wales, and almost the whole of the mountainous parts of Scotland), and for a few parts of Ireland, geological maps on the scale of 6 inches to a mile have been published; while for many other portions of Britain MS. copies of geological six-inch maps can be consulted, and copies can be purchased through the Geological Survey Offices in London, Edinburgh, and Dublin.¹ For some areas Horizontal

¹ A List of Memoirs, Maps, Sections, etc., published by the Geological Survey, price 6d. (also any of the publications), can be obtained from Mr. E. Stanford, 12, Long Acre, London; Messrs. W. and A. K. Johnston, 2, St. Andrew Square, Edinburgh; and

Sections on a true scale of 6 inches to a mile have been published.

Where possible, a six-inch geological map should be obtained, together with any section and memoir descriptive of the district.

The one-inch geological sheet of the district to be studied is also desirable to show the general structure of the country; and in larger questions, concerning town supplies, the map on the scale of 4 miles to 1 inch is useful in depicting the outcrops and trends of the water-bearing strata over a wide area.

Maps on all the scales mentioned have in certain cases been published in two forms, known as the Drift and Solid editions. In the Solid edition only the main or more regular geological formations are shown, together in most cases with the Alluvial deposits along the river valleys.

In the Drift edition the surface geology is fully depicted, all the superficial deposits of gravel and sand, loam, Boulder clay, etc., being shown, as well as the outcrops of the so-called Solid formations.

Where two editions are published, it may be desirable to have both, especially when deep boring is contemplated, as in certain areas the outcrops of water-bearing strata are wholly concealed by the superficial deposits. It is necessary to know the approximate underground limits of the Solid formations, and whether they are covered by pervious or impervious superficial strata. In the case of shallow wells in Drift, it is of course important to know the nature of the substrata.

Messrs. Hodges, Figgis, and Co., 104, Grafton Street, Dublin; or from any agent for the sale of Ordnance Survey maps, or through any bookseller from the Ordnance Survey Office, Southampton.

In a detailed examination of a district with reference especially to any sources of contamination to springs or wells, it is desirable to check the geological lines even on the six-inch maps, bearing in mind that geological formations are subject to many local changes in lithological character, that water-bearing subdivisions may be wedge-shaped and inconstant, and that some impervious bands affecting springs may not be indicated on the map.

Geological formations, as already mentioned, are often more complex than their names suggest, and it is not possible to represent on maps all their minor lithological subdivisions. Further, it is always possible that some evidence, not available at the time when the map was prepared, may be obtained during a special examination with regard to water-supply

In the first place the geologist has to ascertain the area within which it is desirable to obtain a supply, and the quantity required. As rough estimates of quantity the following may be given :

1. Supply for cottages, 10 to 50 gallons per day.
2. Supply for small houses, 60 to 150 gallons per day.
3. Supply for mansion with gardens and stables, and with extra provision for fire-extinction, which might require a special reservoir, 1,000 to 2,000 or more gallons per day.
4. Supply for school, barracks, hospital, asylum, baths and wash-houses, or manufactory, 5,000 to 10,000 gallons per day.
5. Supply for village and small country town depends on population and occupation. In some localities not more than 15 gallons per head would be required, but usually about 30 gallons is estimated.
6. Supply for town or city, where works should provide

for the growth of population fifteen or twenty years in the future; and in seaside places for the extra number in summer, sometimes double that of winter-time.

In the case of a mansion, Messrs. Merryweather recommend a provision of not less than 30,000 gallons of water to extinguish fires; for this purpose a reservoir or tank may be required, if no pond, lake, or river, be available.¹

In the cases of 1, 2, and 3, and sometimes 4, the sites are usually suggested by the owners or responsible authorities, and the area within which well or boring can be made, or spring utilized, will be restricted. It is of course necessary before any building-site is purchased that the question of water-supply be determined.

If water cannot be readily obtained within the area, it may be less costly to procure supplies from the nearest Water Company's works.

In cases where a large supply is needed, where no site has been selected, and the limits of the area within which it is desirable to obtain a supply are found to yield no promise of success, the more distant sources likely to yield the required supply should be considered and discussed from a study of the geological maps.

In the British Isles, throughout the area of the Secondary and Tertiary formations, there are in most places prospects of supplies from wells or borings at various depths up to 600 feet or more. The most troublesome districts are those in the great vales of Lias, Oxford, Kimeridge and Weald Clays, and sometimes in the Gault Clay.

¹ 'Water-Supply to Villages and Country Houses,' 7th edit.

Among the Palæozoic rocks, where the strata are much denser and often much disturbed, the problems of underground water are more complex and uncertain. Such is the case in areas of Old Red Sandstone, Silurian and Older rocks, and as a rule springs, streams, and reservoirs, are the chief sources of water-supply.

In many areas in Britain shallow local supplies may be obtained from river gravels, from plateau gravels, and from the fissured and shattered surfaces of harder rocks.

When the geologist is fortified with all available geological information, including published records of well-sinkings and borings in the district, the task of ascertaining the probabilities of a supply at any particular spot is greatly facilitated.

If the water-bearing strata are not actually at the surface on the site that may be proposed for a supply, such a site is perhaps more often than not of little importance to the geologist as an aid to his inquiry. Where possible, the well or boring should be on a clay-tract at some little distance along the dip-slope from the outcrop of the water-bearing strata. Direct contamination from the surface is thereby avoided.

The geologist will devote chief attention to the gathering ground or exposed area of the water-bearing strata, to the physical features and natural drainage, as in some cases copious springs may affect the prospects of a good underground supply. Thus, not only the geological position, but the levels of all springs, should be noted. An examination should also be made of the habitations on the porous strata, and to ascertain whether the area of outcrop is liable to pollution from burial-grounds, farming operations, canals, cess-pits,

sewage-works, or waste-water from hospitals. Pollution is sometimes caused from quarries where men are at work, from old excavations where rubbish of all kinds is shot, and from swallow-holes choked partly with mud and dirt where cattle congregate.

Sites for public wells in shallow or in deep-seated porous strata that extend to the surface, should be as far as possible from streams or ponds that may be liable to pollution, and from public roads where the surface drainage is carried away into ditches, and may be conveyed into the strata below. Highly manured arable lands are to be avoided, and the situation should be selected with reference to the probable further growth of the town. It must be remembered that floods are likely to carry polluted water over alluvial flats and into bordering porous or jointed strata; and during heavy rains more pollution may be conveyed into the porous surface-strata from cultivated tracts.

In the case of springs which are recommended by Urban or District authorities for the supply of village or town, a careful examination of a large tract of ground may be necessary, and advice should be given on the area of gathering ground that ought to be protected.

Springs may be subject to contamination when by appearance and chemical analysis they show no signs of it.

It is needful to ascertain the nature, thickness of the rocks whence they issue, and the geological structure of the area.

Drainage from mansions is sometimes carried in pipes across a park into streams that flow over porous strata. At a lower level down the valley a spring may

issue, and derive its water in part from the contaminated sources.

With regard to quantity, local testimony as to the permanence of springs is useful ; but gaugings carried out at different seasons by an Engineer are essential. The deeper springs as a rule are more permanent, and

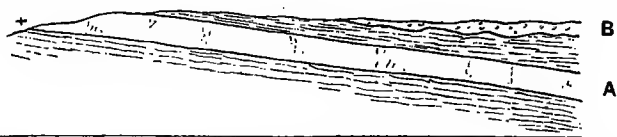


FIG. 36.—DIAGRAM SHOWING STRATA LIABLE TO POLLUTION, AND STRATA FROM WHICH GOOD WATER SHOULD BE OBTAINED.

when they issue from porous rocks that are partly covered by impervious strata, they are less liable to contamination than shallow springs.

In Fig. 36, A is a formation of water-bearing limestone between beds of clay ; B is gravel and sand, also holding water. The water from B, if the ground be



FIG. 37.—INCLINED STRATA FROM WHICH THE SUPPLY OF WATER WOULD BE RESTRICTED.

populated, would be liable to contamination ; that obtained by sinking through B to the limestone A, with the top-water shut out, should be free from pollution.

Deep-seated springs issuing from fissured rocks that extend to the surface over an upland region are, however, liable to contamination, as in the case of the Carboniferous Limestone.

In surface-wells strictly limited supplies are yielded by outliers, as at F in Fig. 21, p. 81, or at H in Fig. 43, p. 297. When the average annual amount of rain is known, the full limit of the possible supply can be estimated. Where the dip of the strata is inclined

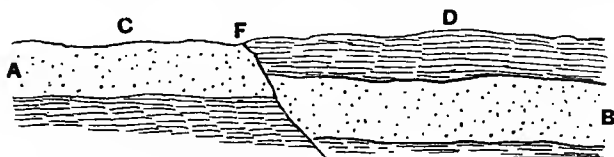


FIG. 38.—EFFECT OF FAULT ON SUPPLY OF WATER.

towards a valley, the porous strata may be largely drained by the outflow of springs, as at the point marked by a cross in Fig. 37, where a formation of permeable sandy limestone B rests on clay A.

Faults may dam up or drain off water, as in Fig. 38,

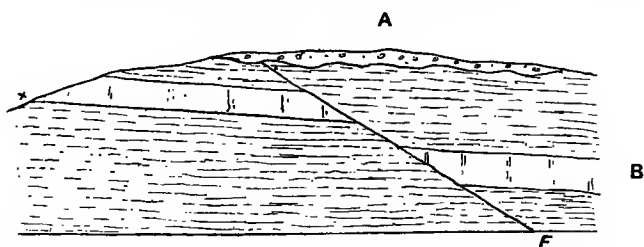


FIG. 39.—CONCEALED FAULT AFFECTING SUPPLY OF WATER.

where below D much water may be diverted from the portion of the water-bearing bed A into that of B, if water is pumped from that side. A well below D, moreover, would be less affected by drought than one at C.

In other cases the water-bearing strata, as in B,

Fig. 39, may be so displaced that a boring will fail to penetrate them if carried below the surface gravel at A; while the pervious bed B on the downthrow side of the fault may be devoid of any supply of water.

Sometimes shattered or fissured limestones may have the interspaces filled with clay from above, thus limiting the inflow and circulation of water. Railway-cuttings may drain away supplies from superficial porous strata in bordering tracts.

For a large town or city more than one boring or reservoir may be required; moreover, it is desirable to make provision for the growth of population, in which

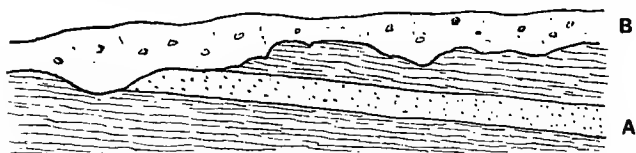


FIG. 40.—BOULDER CLAY AFFECTING UNDERGROUND SUPPLY OF WATER.

case the works are usually planned so that they can be carried out by instalments.

Having gathered all necessary particulars, geological sections should be constructed across the area to show the nature and structure of the gathering ground, the thicknesses and inclination of the strata, the faults, the breadth of outcrop of the water-bearing formation or formations (see Fig. 21), and to what extent the land is covered with Drift clays or loams. Thus, in the case illustrated in Fig. 40, the porous bed A is so concealed by Boulder-clay B as to receive no rainfall.

The consideration of the directions of underground

flow is of great importance in connection with sources of contamination.

In Fig. 41, a site for a well would be preferable to the left side of the village, marked C, towards the scarp, rather than to the right beneath the impervious covering of clay, as any contamination from below the inhabited tract would be liable to travel along the dip-slope of the water-bearing limestone B, if water be withdrawn by pumping on that right-hand side. Better would be a supply from the lower water-bearing limestone A. The outlets of springs are marked by crosses.

The depth at which water-bearing strata are likely to occur at some distance from their outcrop is calculated from local data relating to the thicknesses of the overlying formations, and from a study of the geological structure. The general dip is of course a guide, and this is best ascertained, after the ground has been examined, by the construction of geological sections on a true scale. The contoured six-inch maps of Britain supply the necessary information for the profile, and from them the levels of springs and of outcrops of strata can be fixed.

Local dips in the strata are not to

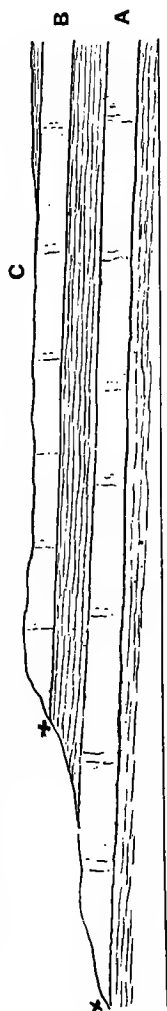


FIG. 41.—DIAGRAM SHOWING SITES FOR WELLS OR BORINGS.

be taken as a general guide to the disposition of the rocks unless there is considerable uniformity; they are often due to very local disturbance.

The following table of the Dip, Incline, and consequent Depth of strata, may be useful:

Angle of Dip in Degrees.			Incline (Approximate).	Depth from Surface in Distance of 100 (Feet or Yards, etc.; as may be reckoned).
1	...	...	1 in 57	1.7
2	...	...	1 in $28\frac{1}{2}$	3.5
3	...	...	1 in 19	5.3
4	...	...	1 in 15	7.0
5	...	...	1 in $11\frac{1}{2}$	8.7
6	...	...	1 in 10	10.6
7	...	...	1 in 8	12.3
8	...	...	1 in 7	14.1
9	...	...	1 in $6\frac{1}{2}$	16.0
10	...	...	1 in 6	17.7
11	...	...	1 in 5	19.5
12	...	...	1 in $4\frac{1}{2}$	21.4
13	...	...	1 in $4\frac{1}{2}$	23.3
14	...	...	1 in 4	25.2
15	...	...	1 in $3\frac{1}{2}$	26.9
16	...	...	1 in $3\frac{1}{2}$	28.7
17	...	...	1 in $3\frac{1}{2}$	30.7
18	...	...	1 in 3	32.2
19	...	...	1 in 3	34.5
20	...	...	1 in $2\frac{1}{2}$	36.6
25	...	...	1 in 2	46.9
30	...	...	1 in $1\frac{1}{2}$	58.0
40	...	...	1 in $1\frac{1}{2}$	84.2
50	...	...	1 in 1	119.0

With regard to quantity, the geologist will be cautious in expressing any definite opinion, leaving as a rule

estimates based on the rainfall and extent of the catchment area to the Engineer. From records in adjacent areas it may be practicable to form a good notion of the amount of water to be expected, while bearing in mind that every additional well will draw upon a supply that is limited. Moreover, the amounts obtained from the same formation in different wells and borings at no great distance apart are subject to considerable variation. The size of the bore-hole will, of course, influence the quantity that can be pumped.

The amount of water likely to be yielded by spring or stream can be gauged; that from a well can only be estimated.

With regard to quality, the geologist can report on the freedom from any apparent source of contamination, and on the prospects of hard or soft water. The mineral ingredients and the question of organic purity are matters for the chemist and bacteriologist.

The following Memoranda and Statistics may be useful to those engaged in prospecting for supplies of water :

1 inch of rain yields 22,622½ gallons per acre, and about 14 million gallons per square mile.

1 inch of rain yields about 100 tons of water per acre.

1 inch of rain yields about ½ gallon per square foot.

1 inch of rain in a year per square mile would yield (if stored) about 38,000 gallons per day.

1 inch of rain in a year per acre would yield (if stored) about 62 gallons per day.

2 inches of rain will supply about 1 gallon per cubic foot to some sandstones and oolites.

4 inches of rain will supply 2 gallons per cubic foot, and practically saturate some sands and Chalk.

A cubic yard of Chalk may thus hold about 54 gallons, and an acre of the same depth rather more than 26,000 gallons.

An English acre = 4,840 square yards, or an area of four equal sides of about $69\frac{1}{2}$ yards.

640 acres = 1 square mile, or 3,097,600 square yards.

1 cubic foot (1,728 cubic inches) of water = $6\cdot232$ or about $6\frac{1}{4}$ gallons, and weighs $62\frac{1}{2}$ pounds (1,000 ounces), at temperature of about 40° F.

32 cubic feet of water weigh 1 net ton (2,000 pounds).

36 cubic feet of water weigh 1 gross ton (2,240 pounds).

The maximum density of water is $39\cdot2^{\circ}$.

1 gallon of water (277·274 cubic inches) weighs 10 pounds (70,000 grains).

1 gallon of water = $0\cdot16$ cubic foot.

224 gallons of water weigh 1 ton.

Note.—The British imperial gallon = very nearly $1\frac{1}{5}$ United States liquid gallons; and 1 cubic foot = about $7\frac{1}{2}$ U.S. gallons.

A stream discharge of cubic feet per minute may be converted into gallons per day by multiplying by 9,000.

Estimates of stream and river discharges are preferably given in cubic feet per second or gallons per day.

Waste-Water.—In country houses there is not only the question of how to get water, but that of how to get rid of the waste-water.

In isolated places the well, the cess-pit, and sewage-tanks, not always water-tight, are sometimes to be found in dangerous proximity; even dumb-wells have been constructed in some instances to convey the sewage into the very strata from which the drinking-water was drawn.

Dr. G. V. Poore has pointed out that the surface

impurities in soil are not dangerous, because the micro-organisms, as in a filter-bed, exercise a purifying influence. Waste products may be put on the soil, but should not be placed in pits dug into porous water-yielding strata.

Divining.—Sites for wells or borings have been selected in many instances by a process that cannot be regarded as scientific, but is sometimes termed Rabbdomancy.

With the aid of a forked hazel-twigg, designated a Divining Rod (*Virgula Divinatoria*, Dowsing Rod, or Jacob's Rod), certain individuals have from time to time undertaken to find water, or rather to indicate where and at what depth it would be found, and 'the rod being properly held by those with whom it will answer,' water has sometimes been discovered in tracts not far removed from sites where previous practical trials had failed in their search.

Some say that the muscles of an individual of suitable nervous organization would act on the Divining Rod, and thus help him to make up his mind concerning the spot that should yield water; others consider that the rod is not necessary, and that the presence of underground water manifests itself on the sensitive organization of the individual.

The power of divining has been attributed to electric or magnetic influences, to changes of temperature and moisture, such as are well known to affect many people on the approach of a storm. In this connection the influence of radio-active emanation has also been mentioned.¹

¹ Review of Dr. E. G. Dexter's 'Weather Influences,' *Nature*, vol. lxxii., June 15, 1905, p. 147.

The subject was discussed very fully by R. W. Raymond,¹ who pointed out that the Divining Rod dates back to the earliest historic times, and was used for a variety of purposes, to prove the site of old landmarks, to detect crime, to guide a traveller in the right course, and, moreover, the Rod being attracted by all metals and in a certain order, it was employed in search of mineral lodes.

Bearing on this subject, it was remarked by Sir Humphry Davy that 'the Charter of the Royal Society states that it was established for the improvement of NATURAL science. This epithet "natural" was originally intended to imply a meaning of which very few persons, I believe, are aware. At the period of the establishment of the Society, the arts of witchcraft and divination were very extensively encouraged, and the word "natural" was therefore introduced in contradistinction to *super*-natural. Although Sir Walter Scott, in his "Demonology," alludes to the influence of this Society in diminishing the reigning superstition, he does not appear to have been acquainted with the circumstances here alluded to.'²

During the past fifty or sixty years Divination for water has undergone a kind of revival, but it has proved notoriously uncertain when from its very nature it should be infallible. Thus, Local Boards and District Councils have spent money on water-diviners who were 'remarkably unsuccessful.'³

¹ In 'Mineral Resources of the United States,' by A. Williams, jun., *U.S. Geol. Survey*, 1883, p. 610.

² 'Life of Davy,' by Dr. J. A. Paris, vol. ii., 1831, p. 178.

³ Report Medical Officer, Loc. Gov. Board, 1905-6. See also discussion on paper by W. Whitaker on 'Some Middlesex Well Sections,' *Trans. Brit. Assoc. Waterworks Eng.*, ii., 1897, p. 31.

Professor C. V. Boys has dealt with the subject, and with some of the preposterous 'scientific explanations' that have been given. Referring to the Diviner, he remarked: 'Of course, if he succeeds in consequence of mere reasoning based upon geological knowledge or experience, while none the less useful to the public, he is, as far as divining is concerned, a fraud.'¹

A Diviner who proceeds without reference to physical features and geological structure may in many cases successfully indicate where water is to be found, and in many cases fail. He appears to base his hopes on the occurrence of underground springs, such as might occur in hard jointed rocks; and there the element of chance comes in. Evidence shows that failures have been about as frequent as successes with the 'Water-finders.' Knowing nothing of the geological structure, or at any rate paying no heed to it, the Diviner may recommend sources liable to contamination, if not grossly polluted, as he does not profess to divine quality.

Nevertheless, in justice to Diviners, it should be mentioned that several men of science, and others, whose good faith was beyond question, have expressed belief in the efficacy of divining, generally from the testimony of others in whom they had implicit reliance.

Definite cases, however, have been recorded where the Geologist has failed, and the Diviner has been successful, in indicating a spot where a water-bearing fissure was met with.²

¹ Review of B. Tompkins' 'Theory of Water-Finding by the Divining Rod,' 2nd edit., 1899; *Nature*, November 2, 1899, p. 1. See also papers by Mr. T. V. Holmes, *Journ. Anthropol. Inst.*, 1897, p. 233; Professor W. F. Barrett, *Soc. Psychical Research*, 1897, and others.

² The subject was discussed by Mansergh (address, 1900).

Geologists in selecting or recommending sites for wells or borings are liable to miscalculation and failure: the thicknesses of the strata may be in excess of the estimate, concealed faults or overlaps of strata may interfere with the underground circulation, and fissures which should yield a supply may not be encountered.

Nevertheless, as the mode of occurrence of underground water is dependent on geological structure and the nature of the rock-formations, so it is evident that the opinion of a geologist, in our present state of knowledge, should be better than that of one who professes to have the gift of divination.

As Professor Boys remarked, we want a better quality rather than quantity of evidence to be satisfied of the reality of divining.

All underground water is not flowing unless there be a natural exit or water is abstracted by pumping, and yet it is said that stagnant water is not indicated by the Divining process.

One of the latest advertised devices is an 'Automatic Water Finder,' which is supposed to work through the influence of electric currents, that are strongest in the vicinity of subterranean water-courses. No evidence of its success has come before us.¹

RESPECTING QUANTITY AND SUPPLIES FOR DIFFERENT PURPOSES.

It is difficult to estimate the quantity of water that can be drawn from a formation, owing to the varying thicknesses of the strata and their varying capacity for holding and transmitting water. The loss by springs

¹ See questions in *Nature*, October 14 and 28, 1909, pp. 456, 518.

and by pumping has also to be considered, so that the yield of water in one district is no guide to the water-bearing capacities of the same formation at a distance.

In reservoir sites it is possible to estimate more nearly the actual supply that can on the average be relied upon, as the area of the gathering ground may be fairly well defined; but, as remarked by J. Mansergh (1882): 'It is seldom safe to prophesy what a given well or boring will yield.'

Water is required for—

Domestic or Household Purposes: For drinking, washing, cooking, lavatories, stables, gardens, and (in mansions) for the extinction of fires.

Municipal Purposes: Flushing sewers and watering and cleansing streets, extinguishing fires, public lavatories, baths and wash-houses, drinking-fountains, parks and ornamental waters, workhouses, asylums, etc.

Industrial and Professional Purposes:

Chemical works, breweries, aerated water manufactories. Railway-works, electric power stations, hydraulic lifts, canals, and other engineering works.

Paper-mills, flour-mills, tanneries, soap-works, and various textile factories.

Agricultural purposes, dairies, irrigation, nurseries and market-gardens, stables.

Laundries.

Hotels, schools, and colleges.

The following statistics of the daily supply in gallons per head of population are given in round numbers, from the paper by Mr. Baldwin-Wiseman (1909):

Daily Supplies of Water to Towns, per Head of Population.	Gallons.	Year.
Basingstoke	36	1906
Birmingham	$26\frac{1}{2}$	1907
Bournemouth	$26\frac{1}{2}$	1906
Bradford	40	1906
Brighton	35	1906
Cardiff	26	1906
Chester	35	1906
Derby	$24\frac{1}{2}$	1908
Dorking	$19\frac{1}{2}$	1906
Dover	27	1907
Gloucester	20	1906
Guildford	30	1906
Hull	$35\frac{1}{2}$	1906
Ipswich	20	1907
Leicester	16	1906
Lincoln	$29\frac{1}{2}$	1907
Liverpool	$32\frac{1}{2}$	1906
London	33	1906
Manchester	32	1908
Margate	29	1906
Nottingham	22	1907
Peterborough	43	1906
Reading	$40\frac{1}{2}$	1906
Ripon	26	1906
Rugby	27	1906
St. Albans	$29\frac{1}{2}$	1906
Scarborough	$31\frac{1}{2}$	1908
Sleaford	21	1906
Southampton	40	1906
Stamford	15	1907
Swansea	41	1906
Tonbridge	22	1907
Torquay	$33\frac{1}{2}$	1908
Tunbridge Wells	27	1906
Warminster	21	1906
Whitehaven	$62\frac{1}{2}$	1906
Winchester	32	1906

The average daily amount used per head in Great Britain has been estimated at 33 gallons.

The consumption naturally varies in each locality according to the season, more being used in the summer months, especially at seaside and inland watering places. The use of a bath may require from 20 to 40 gallons.

It is usually reckoned that manufacturing towns require more than agricultural, but in many cases the factories and industrial works are supplied independently by wells.

Large quantities of water are required in various industries and for municipal purposes, as noted by Mr. Baldwin-Wiseman (1909). Thus, in extinguishing fires in large cities, from 12 to nearly 30 million gallons may be used annually, as much as 27 million gallons having been used in London in one year.

The railway companies in England and Wales in 1907 required more than 10,000 million gallons of water.

Breweries have been estimated to use from 10 to 14 thousand million gallons per year, during the past seventy years, but the amount seems likely to decrease.

Paper-mills, according to Mr. C. Beadle (1908), require from 10 to 200 thousand gallons per ton of paper manufactured, but the water, so far as possible, is purified and used again.

Mr. Whitaker (1908) remarked that the largest public supply obtained solely from wells has been that of the Kent Water Company (now part of the Metropolitan Water Board), which has drawn more than 20 million gallons a day from the Chalk.

With regard to particular wells, as much as 3 million

gallons a day have been pumped from the Great Oolite near the Thames Head ; $2\frac{1}{2}$ million gallons per day from the Bunter Beds in Lancashire, and 5 million gallons from the Lincolnshire Limestone at Bourne. At Passy, near Paris, an artesian well, 1,923 feet deep, has yielded more than 5 million gallons a day, afterwards $3\frac{1}{2}$ million, from the Lower Cretaceous sands.

In Florida, a well at St. Augustine, 1,400 feet deep, is stated by Slichter (1902) to yield 10 million gallons a day ; while in South Dakota a well 725 feet deep has been reported to yield as much as $11\frac{1}{2}$ million gallons a day. (See also pp. 256, 258.)

CHAPTER XIII

MISCELLANEOUS SUPPLIES OF WATER IN POLAR, ARID, AND OTHER REGIONS AND ISLANDS

IN those parts of the Polar regions where the ground is permanently frozen, all supplies of water have to be obtained from snow or glacier ice by boiling, or other means of melting. In certain parts, from June to August, streams or ponds of fresh water may be found, as in Spitzbergen. Nansen, in his 'First Crossing of Greenland' (1892), carried tin flasks which were filled with snow or ice, that could be melted by the heat of the body. Alcohol was then recommended for use in boiling apparatus, but petroleum was used in his expedition 'Farthest North' (1897).

In old times whaling vessels obtained supplies by melting blocks of fresh-water ice, obtained in many cases from ice formed from liquefied snow on the surface of salt-water ice. The latter, as remarked by Sir John Richardson, contains salt in crystals, and sometimes in layers of considerable thickness.¹

In Northern Siberia and Alaska the ground is frozen in places to a depth of about 100 feet in winter, and the thaw in summer extends only a few feet.

¹ 'Polar Regions,' 1861, p. 229,

Professor H. A. Miers notes that the gravels along the creeks or gulches in the Yukon district are covered by a layer of peaty vegetation sometimes more than 10 feet thick, which keeps the gravel beneath it permanently frozen throughout the summer; indeed, sheets of solid ice are preserved in the gravel.

Much of the earlier work of gold-mining was carried out by thawing the gravel with wood fires in the winter, and washing the material in the summer when water was available. In place of these and other tedious processes, steam-thawing was introduced, the steam being forced into the gravel at high pressure. A newer method was to thaw the ground by means of water forced into it by means of a pulsometer pump, a process which allowed the water to be used again and again.

Hydraulicking has since been introduced, the water being derived from a reservoir, and pumped to a tank that gives a fall of about 60 feet. Most of the work is now abandoned in the winter.¹

In an account of the construction of the Jungfrau Railway, Mr. F. Oederlin remarked that at Eiger-gletscher, 7,260 feet above sea-level, all water was frozen between November and May, and the supply required was only to be obtained by an electrical melting process.²

Water-holes are natural or artificial excavations into which water infiltrates. The term is usually applied in arid regions where streams flow but temporarily in the creeks, and rain sinks rapidly into the porous soil and

¹ 'A Visit to the Yukon Gold-Fields,' 1901.

² *Journ. Manchester Geog. Soc.*, xxiv., 1908, p. 139.

substrata. Thus, along the deeper portions of a river-course in times of drought, pools that mark the plain of saturation may exist here and there, while other isolated pools may receive a certain amount of the drainage from large tracts of sand and gravel. Many water-holes are simply dug-wells.

Professor J. W. Gregory (1906) refers to crescent or horseshoe-shaped hollows, 'ox-bows,' that once formed part of a main river channel, and now constitute here and there an isolated water-hole, or 'billabong,' as it is termed in Australia.

Some water-holes are large lake-like expansions, others are but the size of ordinary wells, and in desert regions they may be so far apart that the traveller has need to carry water-bags. Occasionally water-holes only a foot or two in depth may last a long while, but all are liable to contamination from dead animals, etc., and it is desirable to boil the water before drinking. Water is often obtained by digging holes along the courses of creeks or dried river-beds, or on sandy plains that are periodically flooded. A spiked rod may be useful in piercing the soft ground to ascertain if water be within easy reach.

'Soakages,' as described by Professor J. W. Gregory (1906), are temporary wells or water-holes dug in a low plain bordering a river, or on lines of drainage into saline pools or water-holes. They often yield fresh water on the edge of a brine pool, as at B in Fig. 42, when fed by drainage from a large area of sandy strata with clayey inter-



FIG. 42.—DIAGRAM OF WATER-HOLE. AFTER PROFESSOR J. W. GREGORY.

calations, A. Professor Gregory refers to a lake at Kilalpaninna that is saline when low, and fresh when full.

Rock Reservoirs.—Among water-holes are those described by Joseph Thomson under the name of ‘Ungurungas,’ or rock-basins, in British East Africa. In the vicinity of the Taro (Taru) Hills, there are tracts of sandstone weathered along the joints into deep trenches 18 inches to 2 feet broad, which form natural reservoirs for rain-water. The surfaces of the sandstone are also weathered here and there into pot-holes of all sizes, from 18 inches to 2 feet in diameter, and up to 8 feet in depth. These are formed to some extent naturally by the weathering agencies of rain and wind, and have been enlarged in some instances, probably, by man.

Thomson mentions an instance of one of these rock-reservoirs at the top of Maūngū that ‘never dries up, and which formerly supplied the necessities of several villages.’¹ This calls to mind the features of a dew-pond. (See p. 108.)

Among minor features, the tors of Dartmoor, formed of natural granite blocks, exhibit many shallow circular and oval ‘rock-basins’ from 10 to 54 inches in diameter and from 2 to 7 inches in depth, as measured by G. W. Ormerod.² These are due to the decay of the granite, which here has a globular or nodular structure.

Oases.—The oases in the Great Desert of Sahara consist of hollows, sometimes of great depth and extent, that have been carved out mainly by the erosive action

¹ ‘Through Masai Land,’ 2nd edit., 1887, pp. 37, 41. I am indebted to Dr. Walcot Gibson for the reference.

² *Quart. Journ. Geol. Soc.*, xv., 1859, p. 16.

of wind carrying sand—in some instances nearly to sea-level. In the Libyan Desert on the east, where they are bordered by the cliffs of the plateau, which rise from about 650 to more than 1,200 feet, many are due to anticlinal flexures which may have been to some extent planed down, as Dr. W. F. Hume points out,¹ by the sea on the uplift of the strata, and the softer strata thus revealed were acted upon by wind-drifted sand.

Some of the smaller oases, as Farafra Oasis, occur in the higher Cretaceous limestones, while the larger ones are found in the older Nubian Sandstone. There the succession is given by Mr. H. J. L. Beadnell (1909)² as follows :

Surface-water sandstones	...	About 150 feet.
Grey shales	... ..	... „ 240 „
Artesian water sandstones	...	... „ 390 „

The Libyan oases are mostly supplied with water from wells and borings ; among them the Kharga Oasis is about 115 miles in length, with a breadth of from about 12 to 50 miles.

At the time of the Roman occupation, 30 B.C. to beginning of seventh century, much water was obtained from fissures in the Surface Water Sandstone by means of long underground collecting tunnels, with airshafts excavated in the solid rock.

It is not known when the flowing wells were first made, but the occupation of some of the oases dates back to Palæolithic times, when perhaps natural springs furnished a supply of water. The main supplies are obtained beneath a mass of shales from the Artesian

¹ *Cairo Scientific Journ.*, ii., August and September, 1908.

² See also Beadnell, *Geol. Mag.*, 1908, pp. 49, 102.

Water Sandstone, whence flowing wells are derived, usually as soon as the top of the lower sandstone is reached. The water is derived, possibly, to some extent from rains in the Sudan or on the mountains of Abyssinia, probably to a large extent directly from the Nile in Nubia.

The floor of the Kharga Oasis, as described by Mr. Beadnell, is from 170 to nearly 200 feet above sea-level, and near the static head or limit to which the water will rise. At the present day there is no natural outflow of artesian water, but many ancient wells, some dating back to from 1000 to 3000 B.C., and about 400 feet in depth, continue to flow, and at the rate of several hundred gallons a minute night and day. The outflow is seldom more than 10 or 15 feet above the surface of the ground.

Flowing water is now usually obtained as soon as the drill strikes the top of the Artesian Water Sandstone. More than 300 gallons per minute may be obtained at first, but the amount soon becomes less. The temperature is 86° to 88° F. Ordinarily the water contains from 30 to 33 grains per gallon of saline matter, chiefly lime and magnesium sulphates and some iron-salts.

The largest well in Kharga Oasis has a discharge of between 700 and 800 gallons per minute, but there are many discharging less than half that quantity, and some only 20 or 30 gallons per minute. The total outflow is reckoned at about 11½ million gallons daily.

Experiments have shown that the shutting down of a flowing well or the opening of a closed one may produce a very marked effect on another well more than 600 yards distant, and in a period of an hour.

Pits or collecting tanks are sunk into the Surface

Water Sandstone for irrigating purposes, as bore-holes in the rock yield too slow a supply.

The Kurkur Oasis, described by Dr. John Ball, is formed by the confluence of several wadies or drainage channels, and has no outlet.

In the Sudan south of Khartoum, the Cotton soil district, as pointed out by Mr. G. W. Grabham,¹ requires special conditions for a successful well. The soil is fine-grained, and absorbs a large amount of water; but it is impervious, though fissured in the dry season with wide cracks often 6 feet deep. Well-water has been obtained where the blanket of Cotton soil is pierced by an island or inlier of decomposed igneous rock. There water is found at various depths up to 50 or 60 feet, by wells sunk or occasionally driven into the hillside.

Towards the borders of the Red Sea, where the ground is occupied by crystalline rocks, and contains deep valleys filled with gravel and detritus, the streams carry much sediment during heavy rain, and water is absorbed rapidly by the porous bed. As the flow diminishes the stream-bed becomes clogged with mud, infiltration is checked, and pools remain at a level above that of the water-table in the valley deposits. As Mr. Grabham remarks: 'It appears, then, that the rate of percolation from a stream into its bed is a function of the size of particle it can carry in suspension, and, consequently, of the speed of the current.'

The water in the river deposits, protected from evaporation, flows down the valley, and is readily tapped by wells. At one point where the rocky valley

¹ *Geol. Mag.*, 1909, pp. 265, 311.

is restricted the underflow cannot pass, and the water forms a stream at the surface.

Along the margin of the Red Sea there is a plain composed of gravelly detritus brought down from the hills, deposits which have been proved by boring to attain a thickness of more than 1,000 feet. The underflow from the rocky valleys traverses these deposits, which receive also local rainfall and flood-waters from the hills. A considerable quantity of saline matter is brought by the underflow from the valleys. Hence some wells have yielded fairly good water, others variable amounts of chloride of sodium, etc.

The best water is obtained at the upper part of the zone of saturation, and as a rule in the coarser-grained deposits, Mr. Grabham remarking that the finer-grained strata (as has been elsewhere noted, see p. 300) tend to cause a concentration of salts. In some cases the flood-waters take up saline matter that has been deposited on the surface after evaporation of water raised by capillary action. Thus, various influences have caused differences in the well-waters, some near the sea being less saline than those far away. A few of the more saline waters, with 3,000 parts per million of solids in solution, have been successfully used for irrigation.

In areas of Nubian Sandstone wells up to 200 or even 300 feet in depth have yielded supplies, usually derived, in Mr. Grabham's opinion, by seepage from the Nile, which takes place for the most part during the flood, when the river is high and the rapid current keeps free the pores in the sandstone. The cemented tanks on the hills in the Sudan are termed Hafirs.

At Aden a series of reservoirs at successive levels has been constructed above the town. These are

capable of holding 12 million gallons of water, but are completely filled only about once in two or three years.

In Rhodesia, as noted by Mr. F. P. Mennell, supplies are obtained from wells at a depth of about 60 feet, the water percolating through the soil and broken and fissured surface-rocks. There is no general body of water in the area.

Elsewhere the permanent streams, or large water-holes, and embanked reservoirs, known as 'dams,' filled during the rainy season, are the only reliable sources of water.¹ Bulawayo is supplied from reservoirs. Kimberley is supplied from the Vaal River.

Copious springs issue from the dolomitic rocks (cherty limestones), which form some of the head-waters of the Vaal River south of Johannesburg.

At Magila, in German East Africa, rain-water is stored underground in stone tanks, as I am informed by the Ven. Archdeacon H. W. Woodward.

In Australia immense supplies of underground water have been obtained from the Jura-Trias sandstones, and in part from Lower Cretaceous sandstones in the central plains of Western Queensland, New South Wales, and South Australia. The sandstones, which are often pebbly, rest in a great basin of older crystalline rocks, and are covered by impervious clays and loams.

In Queensland artesian water has been obtained in the northern area, south of the Gulf of Carpentaria, at depths of 2,000 feet and more, with a yield varying from 100,000 to 1 million gallons a day.² In central

¹ 'Rhodesian Miners' Handbook,' 2nd edit., 1909, p. 147.

² W. E. Cameron, *Rep. Geol. Survey Queensland* for 1900.

Queensland, at Blackall, at a depth of 1,645 feet, or 774 feet below sea-level, artesian water was found, as noted by Professor J. W. Gregory (1906), and it flowed to the surface at the rate of nearly 300,000 gallons a day. A boring at Bimerah is stated to be 5,046 feet deep.

In the northern territory of South Australia, near Cape Ford, Anson Bay, a boring for coal was unsuccessful, but at a depth of 1,050 feet fresh-water, which rose to the surface, was encountered; and at 1,374 feet the flow increased to 1,600 gallons per hour. The strata passed through were sandstones alternating with shales.¹

Port Darwin is supplied from a reservoir and tanks which receive water during the rainy season.

Borings in the vicinity of Lake Eyre have been carried to various depths up to 3,000 feet, and the yield has been as much in some cases as 1 million gallons a day.

Professor J. W. Gregory (1906) has recorded that in 1904 nearly 400 million gallons of water a day were derived from artesian wells in Queensland, and 54 million gallons a day from wells in New South Wales.²

In some instances the water comes up hot and steaming, and is impregnated with sodium salts, but not always in too great quantity to prevent the thirsty traveller from making tea.

Considerable discussion has arisen concerning the origin of the Australian artesian waters. It is more generally held that they are due to the rainfall on the

¹ H. Y. L. Brown, 'Reports on Recent Mineral Discoveries,' 1908, p. 10.

² See also E. F. Pittman, *Journ. Roy. Soc. N.S. Wales*, xli, 1908, p. 100.

mountainous districts that border the desert areas, as in the eastern highlands of Queensland, where there is an abundant rainfall; and, as noted by Professor Gregory, the rivers dwindle westwards, part of the water percolating underground, part being evaporated.

Taking into account the distance to which the underground water must travel, the slowness of transmission through the sandstones, the loss of pressure due to friction, and other causes, Professor Gregory has been led to question whether the underground water can be entirely due to the rainfall, and has suggested that much water has been derived from plutonic or magmatic sources. (See p. 304.)

In some tracts there has been a noticeable decrease in the outflow of wells, and it is admitted as highly probable that they are discharging past accumulations of water. Under these circumstances it seems necessary that the waste of water from some flowing wells should be stopped—a subject to which serious attention has been called.

Western Australia comprises a coastal plain formed of sandstones, conglomerates, shales, clays, and occasional limestones, bordered by hill-ranges which rise in places to 4,000 feet above sea-level. The interior, which includes the chief mineral region, consists mostly of a broken tableland of desert sandstone and extensive sand plains, with saline depressions or salt marshes and clay flats or pans, with no rivers and but little and irregular rainfall.

In districts bordering the coast, water is obtained from springs, streams, and shallow wells. Artesian water is also obtained from the coastal strata, along the south-western and western tracts, for the most part

from inclined strata that form one side of a syncline, and occasionally from a synclinal basin. Where the strata dip seaward, the fresh-water is sometimes banked up by sea-water. From sixteen flowing wells, of varying depths up to 1,860 feet, a total yield of more than 4,800,000 gallons has been obtained per day, while three non-flowing (sub-artesian) wells have yielded together more than 500,000 gallons per day.¹

Much water is thought to escape to sea from the desert regions bordering the south coast, and Professor J. W. Gregory (1906) has noted that fresh-water springs rise through the sea on the borders of the Great Australian Bight. (See p. 92.)

The sand-dunes on the coast yield good supplies in places.

The gold-fields of Coolgardie and Kalgoorlie have been supplied with fresh-water from the coast, pumped at successive stages, and transmitted for a distance of 308 miles and to a height of 1,290 feet, whence water is supplied by gravitation. In 1906 more than 600 million gallons of water were used.²

At one time a boring was put down in granitic rock to a depth of 2,000 feet at Coolgardie, and it is not surprising that no water was encountered.

In some tracts where the only supply of water is saline, condensing apparatus has been used, and dams have been constructed to conserve the rain-water.

Irrigation.—In arid regions, or those where the annual rainfall is below 18 inches, or where the rain is

¹ Harry P. Woodward, 'Mining Handbook to the Colony of Western Australia,' 2nd edit., 1895; A. Gibb Maitland, Bulletin No. 4, *Geol. Survey Western Australia*, 1900, p. 129, etc.

² F. D. Johnson, *Mining Journal*, 75th Anniversary No., 1909, p. 37.

periodic or uncertain, water-supplies are required for purposes of irrigation. In some cases the supplies may be obtained from streams at higher levels, from reservoirs, or from wells. In India all sources have been utilized.¹

As a rule, however, well-water and deep artesian water will only supply limited areas, and storage is requisite for extensive works. Warm waters have sometimes been used, and in Egypt saline waters, but these are not always suitable. (See p. 254.)

Water is required in the great plains of Arizona, Nevada, and Utah, and in California. Abundant supplies of water come from the melting snows of the mountains and during the rainy season, but otherwise the stream-flows are insufficient. The problem is to obtain good reservoir sites. As noted by Mr. A. L. Fellows, it will take approximately 2 acre-feet, or 2 acres covered with water 1 foot deep, to irrigate a single acre of land for a season, so that to irrigate 1,000 acres would require a reservoir of about 100 acres 20 feet deep.²

Slichter (1892) mentions that subsurface or submerged dams carried through Alluvial strata to the bed-rock, so as to arrest the underflow, may be useful in forming underground reservoirs in the upstream gravels for irrigating purposes.

Water-conduits or flumes, described by Rafter (1903),

¹ 'Irrigation in India,' by H. M. Wilson, 2nd edit., 1903. Water-Supply and Irrigation Paper, No. 87, *U.S. Geol. Survey*; see also 'Irrigation Geologically Considered, with Special Reference to the Artesian Area of New South Wales,' by E. F. Pittman and T. W. E. David, *Journ. Roy. Soc. N.S. Wales*, xxxvii., 1908, p. ciii.

² Water-Supply and Irrigation Paper, No. 74, *U.S. Geol. Survey*, 1902, p. 19.

are sometimes constructed in porous strata below the normal level of the ground-water, for the purpose of collecting and delivering water at the surface for mining works lower down the valley. The flumes, about 4 feet deep and 5 feet wide, are covered and provided with wooden sides, but are open at the base. In the mining of surface or placer deposits, water-power is used for ground-sluicing, and, under pressure, for 'hydraulicking.' (See p. 248.)

Islands.—In the Scilly Isles, as noted by Mr. George Barrow, the water-supply is obtained chiefly from rain-water collected on roofs and stored in underground tanks. With the exception of one small runnel there are no streams.

Wells have been sunk in places not far from the sea, and below its level, in superficial deposits and decomposed granite. The water rises and falls to some extent with the tide, and yet appears to be quite fresh.¹

Jersey and Guernsey are supplied by wells and springs, water being held in the decomposed igneous rocks. Jersey also has reservoirs for the supply of St. Helier. (See pp. 140, 224.)

Many small islands are supplied by water from land-springs, shallow wells, and rain-water tanks, as at Valentia Island. St. Kilda has one or two rivulets, and many springs and wells.

In the Canary Islands springs issue from the decomposed basalt rocks, and are utilized by means of aqueducts and reservoirs, as at Madeira. Sometimes, as in Fuerteventura Island, there may be little or no rain for a period of three years. Water is obtained

¹ 'Geology of the Isles of Scilly,' *Mem. Geol. Survey*, 1906.

from the river-bed near Antigua and elsewhere, by means of wells and water-wheels.

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Gibraltar, which consists of highly inclined limestone, with some shale, has long been troubled about a supply of water. The ground rises to a height of 1,370 feet, and has a breadth of 1,550 to 550 yards. There is little storage of water in the strata, but now 'a large portion of the rock has been covered with corrugated iron on a wood backing. The iron quickly radiates its heat, and the wood backing acts as a non-conductor. The consequence is that the warm moisture-laden winds coming off the sea are chilled by contact with the iron, and aqueous vapour is deposited on its surface.'¹

Camping Grounds.—In camping grounds for armies, water may sometimes be obtained from hillside springs; but where a broad river-valley is occupied, it is necessary to take water as far above camp as practicable, and to provide latrines on the river-borders below the camping ground to prevent pollution. Water may preferably be obtained from shallow excavations in the valley gravels bordering the stream or river, where it has undergone a certain amount of filtration.

The term **Watering Place** was applied to situations where boats could obtain fresh-water for use on board ship, as well as to Inland resorts or Spas where medicinal waters were drunk, to Seaside bathing-places, and to pools where cattle could drink.

Springs issuing from the Chalk near the Thames at Gravesend were utilized in old times by ships, as I am

¹ G. Hubbard, *Geograph. Journ.*, August, 1909, p. 193.

informed by Mr. Whitaker. In early days in New York, when the city was dependent on local supplies from wells, about 1,400 hogsheads of water were daily brought in from country wells to supply vessels. Small trading vessels, coasting steamers, and yachts, are naturally dependent on land-supplies, but in the larger passenger steamers and in those of the Navy supplies are obtained by the distillation of sea-water, with apparatus for aerating the drinking-water.

Water-Power.—Water under high pressure is conveyed in mains for working lifts and other purposes, the supply taken from ordinary mains being dealt with by machinery (accumulators) which intensify the power. In electric power works, where much water is used, the steam is condensed, and part of the water can thus be used over and over again.

Natural sources of water-power derived from rivers, lakes, and reservoirs, where a fall is obtained, or from waterfalls, such as those of Niagara and Foyers, are utilized for various industrial purposes. Attention has been drawn to 'the motor erected at Santa Cruz for using the power of the sea-waves; this consists of two wells sunk near the sea-front, in one of which is a float which is raised and lowered by the waves. The float is connected to, and works, a pump in the second well, which forces the sea-water into a reservoir, from which it can be drawn when required.'¹

Sea-Water.—Proposals have been made to bring sea-water (about 10 million gallons a day) to London, for the purpose of watering roads, cleansing sewers, extinguishing fires, and for baths. With regard to

¹ *Nature*, September 11, 1902, p. 485.

watering roads, it has been contended that salt-water dries slowly, and therefore its effects would last. It has been used at Hastings for watering streets, and was tried at Bournemouth; but there the roads on the porous sandy soil became damp, and when dry the saline particles were found to be irritating.

While the question of how to get good water is all-important, the question of how to get rid of superfluous water is by no means devoid of importance, especially in the case of the waste-water of country mansions. (See p. 238.) The unwatering of mines and tunnels, as in the case of the Severn Tunnel, and the removal of water from water-logged and low-lying clay districts, are matters of concern with which the Engineer has to deal.

CHAPTER XIV

QUALITY OF WATER

THE quality of water obtained from surface and underground sources, from spring, river, well, or boring, is of prime importance, although perhaps in the majority of wells no analysis has ever been made.

Deep-seated water is usually regarded as the purest form of underground water, and rightly so; but it is well known that the clearest and brightest water—water that is palatable and sparkling—may be dangerously polluted. This is notably the case in shallow well-water and in some springs.

Rain-water is regarded as the purest form of surface water, and with the smallest amount of solid ingredients, but it requires to be judiciously collected. (See p. 96.)

In determining the suitability of water for a public supply, it is necessary to ascertain by chemical analysis the nature and amount of the salts or mineral matters in solution, and by bacteriological analysis the nature and amount of organic impurity. Chemical analysis alone is insufficient to determine whether a water is free from injurious ingredients.

All waters, from rain-water to the deepest of underground waters, contain in solution a certain proportion of gases and mineral matter, and a potable water of

exceptional purity may contain 30 or more grains per gallon of harmless saline ingredients. As a rule the deeper-seated waters, especially the thermal waters, contain a more considerable amount of saline ingredients than the surface waters.

Next in point of softness to rain-water are the upland surface waters in uncultivated regions, but they are liable to be peaty.

The character of surface waters, of spring and well waters, and that of streams and rivers, depends most largely on the nature of the strata which they traverse. Streams gather mineral matters and impurities along their courses, and underground waters take up mineral matters in solution.

Thus, the average amount of dissolved matter per gallon in springs from the Carboniferous Limestone is 22 grains, from the Magnesian Limestone 46, from the Lias 25, from the Oolites and Chalk about 20 grains, chiefly calcium carbonate.

Springs from the New Red Sandstone are hard if the beds are calcareous or derive their waters through calcareous beds.

The springs from the Palæozoic sandstones and grits yield from 8 to 15 grains of mineral matter in solution, and those from the granitic and metamorphic rocks about 4 grains.

Well-water may be much harder than spring-water, that from the Lias ranging from about 40 to 60 grains per gallon, from the Oolites from 18 to 30 grains, from the Chalk about 20 to 25.

The solid ingredients in Chalk water have proved to be greater as a rule in deep wells than in shallow wells near the outcrop, but the proportion of calcium car-

bonate is greater in the shallow wells, as noted by Mr. R. B. Hayward.¹ In the deeper wells there is a considerable increase in the amount of sodium chloride, while magnesium and potassium salts, especially sulphates, appear.

It has been held by R. Warington² that the deeper strata retain a residue of common salt from the time when the rocks were saturated beneath the sea, and that they receive by underground drainage much saline matter. (See p. 291.)

HARD AND SOFT WATER.

Hardness of water is due to the presence of salts of calcium (lime) and magnesium.

Temporary hardness is produced by calcium and magnesium bicarbonates, and chiefly by the calcium bicarbonate, familiarly spoken of as 'carbonate of lime.'

Permanent hardness is caused by calcium and magnesium sulphates, more frequently by calcium sulphate or gypsum.

The hardness due to calcium bicarbonate is that which causes the tufa of the so-called 'petrifying springs,' and is best known in the household by the deposit of fur or encrustations in tea-kettles and boilers. This hardness to a large extent can be removed by boiling, which disperses a part of the carbonic acid gas whereby the insoluble carbonate of lime is deposited. By boiling for half an hour, hardness may be reduced from

¹ *Trans. Middlesex Nat. Hist. Soc.*, 1887, p. 57: Whitaker, *Trans. Herts Nat. Hist. Soc.*, x., 1898.

² *Journ. Chem. Soc.*, li., 1887, p. 500.

14° to 5°. By distillation, of course, it can be entirely removed, but distilled water requires aeration to render it palatable.

According to the Table of Hardness, known as Clark's Scale, and formulated by Dr. Thomas Clark, each degree of hardness is equal to 1 grain of carbonate of lime per imperial gallon.

One grain of carbonate of magnesia is equal to about $1\frac{3}{4}$ grains of carbonate of lime.

In the Sixth Report of the Rivers Pollution Commission of 1868 (1874), the degree of hardness is given in parts per 100,000. As stated, 'to obtain a numerical expression for this quality of hardness, a sample containing 1 pound of carbonate of lime, or its equivalent of other hardening salts in 100,000 pounds, is said to have one degree of hardness. Each degree of hardness indicates the destruction and waste of 12 pounds of the best hard soap by 100,000 pounds, or 10,000 gallons of the water when used for washing.'

This scale of hardness can be converted into grains per imperial gallon by multiplying the number of parts by 7, and then removing the decimal point one place to the left. Thus, if there be 35.4° of hardness per 100,000 parts, the amount would be 24.78° on Clark's scale.

A hardness of 8° is considered best, but as much as 15° is not regarded as excessive, and 16° or 17° is permissible. Salts of magnesium are undesirable in water for domestic use. A soft-water has less than 6° of hardness; hard-water has more than 12°.

Considerable diversity of opinion has been expressed on the relative merits of hard and soft water for drinking purposes, but statistics relating to health in many

localities where supplies of hard and soft water are used do not indicate any notable difference in the death-rate.

As elsewhere noted, hard-water is required for some purposes of trade, but soft-water is more generally requisite.

The notion that Chalk water is liable to produce gout or calculus is a fallacy. Individuals have removed from a Chalk district sometimes to an area of gravel or sand, where the water is obtained to a considerable extent from deep wells in the Chalk. Chalky sediment, however, is found at times in some supplies of water delivered from Chalk wells.

Soft-waters are to be expected in most upland and moorland districts, among the Igneous and Metamorphic rocks; the Cambrian, Ordovician, Silurian, and Devonian grits and slates; the grits and sandstones of the Yoredale rocks, Millstone Grit, and Coal-measures; in some of the sandstones and pebble-beds of the New Red Sandstone series near the surface; in many areas of Lower Greensand and in some of Upper Greensand; in the Bagshot and Barton Sands; and in most of the superficial Gravels and Sands.

Hard-waters are met with in the Ordovician limestone of Bala, and in the Silurian limestones of Woolhope, Wenlock, and Aymestry; in the Carboniferous and Magnesian Limestones; in the calcareous sandstones of the New Red Sandstone series; in the Lias and Oolitic Limestones; in some areas of the Lower Greensand (Kentish Rag); in most areas of the Upper Greensand; in the Chalk; in the Pliocene (shelly Crag); and in Gravels that are made up in part or wholly of limestone pebbles.

There are several processes for softening water, by which the hardness may be reduced from about 22° to 5° .

That known as 'Clark's process' consists in using a solution of caustic lime or quicklime slaked in water, and forming milk of lime, in the proportion of 40 gallons to 500 gallons of the hard-water holding bicarbonate of lime in solution. The hard-water is added to the lime-water. A part of the carbonic acid from the bicarbonate of lime in the hard-water unites with the caustic lime to form carbonate of lime, thus transforming the whole of the lime salt into carbonate, which, being insoluble, is deposited. The 540 gallons of water is thus left clear and soft.

This softening process is considered to purify the water to a considerable extent from organic matter; moreover, the precipitate of carbonate of lime has a market value. The process is applicable to water containing carbonate of magnesia as well as carbonate of lime.

It is remarked that the softened water in large bulk has the natural pure blue colour of clear and uncontaminated water.¹

A modification of the system introduced by Dr. Clark, devised by Mr. H. Porter, and known as the 'Porter-Clark process,' has the advantage of more completely removing the mineral ingredients for water used by locomotives and engine-boilers in general.²

Sir T. E. Thorpe has pointed out that by storing water in reservoirs a considerable proportion of the

¹ Life of Thomas Clark, M.D. (1801-1867), Professor of Chemistry in Marischal College, Aberdeen, *Dict. Nat. Biography*.

² W. W. F. Pullen, *Proc. Inst. Civ. Eng.*, xcvi., 1889, p. 354.

calcic carbonate or hardness is removed, owing to the dissipation of dissolved carbonic acid.¹

Carbonate of soda, or washing-powder, is used in laundries for softening water.

Soft-waters, including rain and snow water, have been found liable, under certain circumstances, to take up lead from new pipes and cisterns, and to cause more rusting in wrought-iron pipes. In the case of lead the oxide is injurious, but in process of time the pipes may be coated with carbonate of lead, which is insoluble.

It has been found that acids derived from peat in moorland areas are liable to dissolve the lead in pipes, and methods have been introduced of neutralizing the acids in the reservoir water with carbonate of soda, with carbonate of lime, or with slaked lime. A larger proportion of peaty acid is found during rainy weather.²

Dr. J. C. Thresh has remarked that soft-waters containing acid ingredients should not be stored in zinc or galvanized-iron tanks. (See p. 98.)

Soft-waters are more apt than hard-water to take up organic impurities; therefore a moderate degree of hardness is generally to be commended in potable water.

Soft-water is requisite for many trade purposes, for steam-boilers, laundries, textile industries, fulling, dyeing, etc.

Hard-water containing calcium sulphate is desired for brewing pale and bitter ales, but softer water is used in making stout and porter.

Good brewing water is obtained in Durham from the

¹ *Times*, Engineering Supp., May 1, 1907.

² See 30th Ann. Rep. of Loc. Gov. Board, 1900-01, Supplement, 'On Lead-Poisoning and Water-Supplies,' by Dr. Houston. Noticed in *Nature*, 1903, p. 498; 1904, p. 597.

Magnesian Limestone, the presence of carbonate of magnesia not being found objectionable.

At Burton-on-Trent the harder waters used for brewing have been obtained from the Valley Gravels and Keuper Sandstones, that from the Bunter beds having less calcium sulphate. It was estimated in 1869 that 350,000 pounds of gypsum were annually imbibed in the drinking of Burton beer.¹

CHEMICAL ANALYSIS.

It was remarked by E. Frankland (1890),² that 'the *exhaustive* chemical examination of a sample of water is one of the most tedious and troublesome operations known to chemists. It requires weeks, sometimes even months, for its completion.'

When, however, the analysis is desired to determine whether a water is suited for domestic purposes, what is sometimes called a Sanitary Analysis is all that is usually required from the Chemist. The particulars given then relate chiefly to the following subjects:

- Organic carbon.
- Albuminoid (or organic) ammonia.
- Free (or saline) ammonia.
- Nitrites.
- Nitrates.
- Chlorine.
- Oxygen absorbed.
- Total residue or solids in solution.
- Hardness { Temporary.
- Permanent.
- Total.

¹ 'Burton-on-Trent: its History, its Waters, and its Breweries,' by W. Molyneux, 1869.

² See also B. Thompson (1902).

In addition notes are appended, if necessary, with regard to odour, colour, and turbidity.

Analyses are set out in grains per imperial gallon or in parts per 100,000 of water, sometimes in parts per million.

To convert grains per gallon into parts per 100,000, multiply by 10 and divide by 7.

To convert parts per 100,000 into grains per gallon, multiply by 7, and move the decimal point one place to the left.

The following particulars relating to ordinary water analyses are compiled mainly from the writings of Frankland:

Organic Carbon.—The organic matter due to animal pollution is naturally more dangerous than that due to vegetable pollution. Frankland (1890) states that, if the proportion of organic carbon to organic nitrogen be as 3 to 1, the organic matter is of animal origin; if 8 to 1, it is mainly of vegetable origin. More than 0.2 part per 100,000 is undesirable, and in spring and deep-well water it ought not to exceed 0.1 part.

Albuminoid or Organic Ammonia.—As indicated above, the larger the proportion of organic carbon to organic nitrogen, the better. The albuminoid ammonia, derived from water containing nitrogenous organic matter (animal and vegetable), should not exceed 0.015 per 100,000. Water containing as much as 0.03 is objectionable.

Free Ammonia.—Derived mainly from albuminoid ammonia; should not exceed 0.008 part per 100,000. The proportion of free to albuminoid ammonia is important, less danger arising if the amount of the latter is proportionately low.

Nitrites.—If large in quantity, indicate sewage pollution.

Nitrates.—In themselves harmless, yet if large in quantity indicate 'previous sewage contamination.'

Total Combined Nitrogen.—Includes the whole of the ammonia, and that in the nitrites and nitrates.

Chlorine.—The amount usually indicates sodium chloride. Although it may be derived from various sources in the strata, from the atmosphere, and from waste-waters of manufactories, it is a component of urine and other organic matter; and a large quantity may indicate sewage contamination, if other sources are not manifest. The normal amount in unpolluted water is reckoned at 1 per 100,000, and 5 parts in that quantity render the water suspicious and sufficient to condemn it, if no harmless source is recognized.

Large amounts of Albuminoid Ammonia, Free Ammonia, and Chlorine, are signs of bad water.

In some cases it is desirable to test for the presence of poisonous metals, such as lead, copper, arsenic, and barium.

The *Total Residue* (not sediment) left on evaporation, and the estimate of hardness, afford as a rule sufficient information of the saline constituents, but where excessive a detailed analysis is usually made.

Oxygen Absorbed.—The amount of oxygen absorbed may afford some indication of the organic impurity in a water; much, however, depends on the mineral ingredients.

The hardness is dealt with elsewhere (p. 266).

The following table gives the average composition of some unpolluted waters and of sewage :

	Parts per 100,000.				
	Rain-Water.	Upland Surface-Water.	Deep-Well Water.	Spring-Water.	Fresh Sewage.
Total solid impurity ...	2.95	9.67	43.78	28.20	72.2
Organic carbon ...	0.70	0.322	0.061	0.056	4.696
Organic nitrogen ...	0.15	0.032	0.018	0.013	2.205
Ammonia ...	0.029	0.002	0.012	0.001	6.703
Nitrogen as nitrates and nitrites ...	0.003	0.009	0.495	0.383	0.003
Total combined nitrogen ...	0.042	0.042	0.522	0.396	7.728
Previous sewage or animal contamination	42	10	4,743	3,559	—
Chlorine ...	0.822	1.13	5.11	2.49	10.66
Hardness {	Temporary	1.1	15.8	11.0	—
	Permanent	0.5	9.2	7.5	—
	Total ...	0.9	25.0	18.5	—

Previous Sewage or Animal Contamination.—As explained by Frankland (1890), this is a standard founded on the animal matter dissolved in London sewage. 100,000 parts of average filtered London sewage are assumed to contain 10 parts of combined nitrogen (ammonia, nitrates, and nitrites).

A sample of water which contains 0.326 part of nitrogen in 100,000 parts is reckoned at 0.294, allowance of 0.032 being deducted for the inorganic combined nitrogen in rain-water. The amount 0.294 is contained in 2,940 parts of the sewage, and the sample of water is said to exhibit evidence of 2,940 parts of

previous sewage or animal contamination in 100,000 parts.

Reasonably safe water may be that derived from deep wells or deep-seated springs, when the proportion of previous sewage or animal contamination does not exceed 10,000 parts in 100,000 parts of water.

Suspicious or doubtful water is that from shallow well or river which exhibits any proportion of such contamination, and deep-well or spring water containing 10,000 to 20,000 parts. *Dangerous water* contains more than 20,000 parts.

These analyses have to be interpreted in connection with local, physical, geological, and sanitary conditions, but the advice of the Chemist is of primary importance.

Excess of chlorine (as chloride of sodium) may come from saliferous strata (Keuper Marls), from deep-seated springs, or from the sea when near the coast, by infiltration or in spray. In West Cornwall, during strong south-westerly winds the rain may contain as much as 21·8 parts of sodium chloride per 100,000.

Nitrates of potassium and sodium are employed as manure, and may be so derived. (See p. 291.)

A certain amount of ammonia may be obtained from the atmosphere.

Reddish ferruginous deposits are derived sometimes from rusty iron pipes, sometimes from ferruginous earth in cavities or 'pipes' in the Chalk, or from bands of iron-ore in the water-bearing strata. Suspended ferruginous matter is removed by aeration and filtration of water.

The odour produced by sulphuretted hydrogen due to the decomposition of pyrites in the strata is some-

times diminished and finally lost after pumping. It is not uncommon in wells sunk through Lias and Rhætic shales.

Brown colour is due sometimes to peaty water, and an excess of it is apt to render water unpalatable. Turbidity may be caused by fine mud derived from flood-waters.

Dr. J. C. Thresh (1901) has remarked that 'the total amount of saline matter permissible in a drinking water depends in a great measure upon the nature of the salts. No hard-and-fast line can be drawn, but the best waters rarely contain more than 20 grains of mineral matter per gallon. When 100 grains is reached, the water becomes rather of the character of a "mineral" than a "potable" water.'

The more common ingredients are—

Calcium carbonate.

Calcium sulphate.

Magnesium carbonate.

Magnesium sulphate (Epsom or bitter salt).

Silica.

Sodium carbonate.

Sodium chloride.

Sodium sulphate.

Samples for analysis should be collected in the bottles known as 'Winchester quarts.' For directions, see Frankland (1890). The total amount of the saline ingredients is all that is usually required.

BACTERIOLOGICAL ANALYSIS.

Impure water is a cause of certain zymotic diseases, such as cholera and typhoid or enteric fever, and perhaps also diarrhœa and dysentery. Scarlet fever,

though disseminated in milk, is not known to be introduced by means of water. Most serious in past years in this country have been the outbreaks of enteric fever at Worthing, Maidstone, Basingstoke, Lincoln, and at the Fulbourn Asylum, Cambridge.

In the case of the Maidstone epidemic in 1897, the evidence was clear that pollution arose from an encampment of hop-pickers, some of whom suffered from enteric fever. They had been permitted to encamp on ground from which there issued one of the springs that was utilized in the town water-supply. At Basingstoke in 1905 pollution of the water-supply arose through leakage of the town drains into a main or well.

The distance to which contamination may be conveyed is a subject on which much doubt prevails. In open jointed rocks there is no natural filtration, as in the case of the Carboniferous Limestone.

In fine sands, soft calcareous sandstones, and earthy ferruginous rocks, a distance of 100 yards or more may be effective.

In Chalk, pollution may be readily carried through fissures, but it is doubtful if it would extend far in the mass of the Chalk itself.

Dr. J. C. Thresh believes that, in all well-authenticated cases of outbreaks of typhoid fever due to polluted water, the contamination has 'gained direct access to the source of supply or to the water on its way to the consumer.' He knows of no instance where 'the contaminating matter had to percolate through several feet of compact soil before it reached the incriminated water.' He refers to instances due to pollution from manured soils, from farmyard muck, from gravel-pits used as dumping-grounds for refuse, and from a sewage-farm.

Dr. Thresh further remarks: 'The fact of underground water becoming polluted is too often only discovered by a sudden outburst of typhoid fever. Such would probably never be the case were the water submitted to periodical examination. . . . [Here] a bacteriological examination is the more important.'

To determine the source of contamination is often a difficult matter; but recourse may be had in some cases to the methods adopted for tracing the underground courses of streams. (See p. 71.)

In all countries, however, it may be difficult to fix on a spring or site for well or reservoir that would be absolutely free from any possible source of contamination.

Water that gives no indication of contamination by chemical analysis may prove by microscopic examination to contain quantities of minute organisms of injurious nature: pathogenic or disease germs derived from sewage or excremental matter.

'Micro-organisms, being slightly heavier than air, have an invariable tendency to fall, and on that account frequently collect on the surface of water; hence rivers, lakes, and ponds, are constantly being thus contaminated. Micro-organisms in very pure water are not readily disposed to multiply, but traces of decomposing organic matter will induce their reproduction.'¹

The term *Bacteria* is applied to a group of single-celled micro-organisms or microbes which belong to the lowest type of vegetation, and multiply by fission and by spores. It is, however, satisfactory to know that 'The dangerous microbes are in a hopeless

¹ Dr. W. Marcet *Nature*, March 20, 1890, p. 473.

minority in comparison with the number of those which are continually performing varied and most useful functions in the economy of nature.’¹

Most of the bacteria found in water are of a rodlike form, and are known as bacilli—*e.g.*, *Bacillus typhosus* and *B. coli communis* (colon bacillus).

Others more or less spiral in form are *Spirilla*—*e.g.*, *Spirillum* or *Vibrio cholerae*.

Spherical forms are termed Cocci, or Micrococci.

Dr. Thresh remarks that as yet the micro-organisms producing cholera and typhoid fever are the only forms causing special disease that have been identified with certainty in drinking-water.

The *B. coli communis* has been stated by Dr. Kanthack to occur almost everywhere, and that it does not in itself prove sewage pollution; but, as remarked by Dr. Thresh, it is regarded by some authorities as capable under certain conditions of acquiring pathogenic properties in man, and thus a large number would rightly lead to the condemnation of the water that contained them.

With regard to the typhoid bacillus—*B. typhosus*—Dr. A. C. Houston reported in 1908 to the Metropolitan Water Board that weekly examinations of raw Thames, Lea, and New River waters during a period of twelve months failed to reveal the presence of a single example.

Sir T. E. Thorpe has remarked: ‘It is clearly established that organisms known to be pathogenic have no chance in the struggle for existence with bacteria which are normal to natural water, and, given

¹ See Dr. A. Macfadyen, *Nature*, February 7, 1901, p. 359; Macfadyen and J. E. Barnard, *ibid.*, November 1, 1900, p. 9; Dr. A. A. Kanthack, *ibid.*, December 31, 1896, p. 209; Professor J. G. McKendrick, *ibid.*, December 16, 1909, p. 207.

time and exposure to light and air, they succumb and disappear.'¹

Recent experiments and observations by Dr. Houston show that the storage of raw water in reservoirs has great advantages in eliminating the typhoid bacillus and the cholera vibrios, in the very considerable reduction of *B. coli* and of bacteria in general, and in the subsidence of matter that tends to block the filter-beds.²

Storage for a period of thirty days is recommended prior to filtration.

London sewage contains from 3 to 6 millions of bacteria per cubic centimetre, an average of about 300,000 per drop. From Barking to Greenhithe the Thames water, which receives the sewage, contains from 35,000 to 10,000 per cubic centimetre. Between Twickenham and Sunbury the number is from about 3,000 to a little over 5,000.³

The number of bacteria in water has been reckoned as a measure of organic purity or impurity, and water is considered very good if the number does not exceed 100 to the cubic centimetre. This test, however, is regarded as of no great value, because the important point is the character of the micro-organisms.

Dr. P. F. Frankland has stated that 'experiments have shown that, although the living bacteria in ice are considerably less numerous than in the water from which the ice has been derived, still the process of freezing, even if long continued, affords no sort of guarantee that the dangerous forms originally present

¹ *Times*, Engineering Supp., May 1, 1907.

² Reports to Metropolitan Water Board, *Nature*, August 20, 1908, p. 377; May 6, 1909, p. 286; August 26, 1909, p. 269.

³ F. Clowes, *Nature*, June 7, 1900, p. 132; September 20, 1900, p. 191.

in the water shall have been destroyed. Thus, the bacillus of typhoid fever has been found still alive in ice which had remained continuously frozen for a period of 103 days.¹

There is no doubt that good water is necessary for ice-supply; but it has been observed by Mr. M. O. Leighton (1903) that a large proportion of foreign matter is excluded in the formation of ice, and that recent investigations tend to show that disease germs do not long exist in it.

With reference to the sewage contamination of oysters, Dr. H. F. Parsons has remarked that 'he thought consumers might not trouble about oysters so long as they knew that they had been kept in pure water just previous to being sold.'²

Sewage Works.—It has been the custom in many of the earlier Sewage Farms to distribute the effluent by irrigation over a certain area of ground before discharging it into a stream or river. Suitable ground was obtained in many areas where there were tracts of valley gravel resting on clay, and with a good depth of top soil; but in all cases the depth of soil and the character of the subsoil or substrata were not satisfactory as regards possible contamination of underground water-supplies.

By the present Bacterial treatment of sewage, whereby the putrescible matters are liquefied and converted into harmless and inoffensive products, the effluents, even without land treatment, may be of quite satisfactory purity. It has even been stated that in rare cases the

¹ *Nature*, November 12, 1891, p. 26.

² *Essex Naturalist*, xv., 1910, p. 256.

sewage effluent after land-treatment might actually be regarded as a potable water of more than average purity.¹

The sediment or sludge can be dealt with by a destructor, or conveyed in barges to sea, or buried. It must be borne in mind that the character of sewage varies greatly in different towns, according to the industries carried on.

In the land-treatment of sewage areas of fissured limestone, sandstone or other water-bearing strata ought to be avoided. Even Chalk and sands should not be utilized for Sewage Farms where well-water is obtained in proximity. The same remarks would apply to Burial Grounds.

The evil of stagnant pools and undrained marshy tracts, especially in tropical regions, has been proved in reference to Malaria. The disease is caused by certain parasites (zygotes), which are conveyed and transmitted through puncture by a genus of Mosquito, known as *Anopheles*.² The larvæ of this insect are developed in stagnant waters, and the drainage of these breeding-grounds, often found in the midst of inhabited regions, is of great importance.

Stagnant pools, moreover, are undesirable in the neighbourhood of shallow wells.

It is remarkable that the fact of malarial fevers being caused by the bite of mosquitoes was suggested in one of the books of the Hindus written about 1,400 years ago.³ Moreover, the decline and fall of the empires

¹ See Interim Report, Roy. Com. on Sewage Disposal.

² Major Ronald Ross, *Nature*, March 29, 1900, p. 522, and June 3, 1909, p. 415.

³ *Nature*, December 9, 1909, p. 158.

of Greece and Rome have been attributed to some extent to the introduction of malaria.¹

With regard to other diseases due directly or indirectly to impure water, some may be purely local or endemic if caused by constituents in the supply. On this subject much has yet to be ascertained.

Ferruginous waters have been regarded as a possible cause of goitre in the Middle Lias ironstone district of the neighbourhood of Banbury, and in the Lower Greensand area of West Sussex, which locally contains a good deal of iron-ore. The cause of the disease has, however, yet to be demonstrated.

The question of purifying water on a small scale is sometimes of importance.

Boiling for half an hour is sufficient to destroy micro-organisms. In olden times it was a question on board ship how to prevent the drinking-water from becoming putrid, and it was found that it could be 'rendered sweet and pure by means of charcoal powder and quicklime,' the charcoal rendering the water sweet, while the quicklime was found to precipitate the 'extractive matter,' thereby fining the water and rendering it clear.² This method recalls to mind Clark's process previously mentioned (p. 269).

During the middle of last century filters were in common use in dwelling-houses, sand and charcoal and a small sponge being used, and later on spongy iron and other materials. Filters, however, are practically abandoned in most cases, as owing to neglect they were often positively injurious, and water companies now supply water in a sufficiently pure condition.

¹ W. H. S. Jones, 'Malaria and Greek History,' noticed in *Nature*, December 16, 1909, p. 192.

² J. W. Norie, 'Naval Dictionary,' 3rd edit., 1804, p. 362.

Various 'germ-proof filters' are still supplied for use in country places and abroad, and pocket-filters are supplied for travellers.

River-water naturally requires a certain amount of filtration and purification. It is considered that sand-filtration may reduce the number of micro-organisms to the extent of 97 per cent., according to the thickness of the sand-bed and the slowness of passage. The superficial slimy layer is that in which for the most part the bacterial work of purification is carried on.

Filtering-sand is obtained from different geological formations, notably from the Lower Greensand of Leighton Buzzard. It must be dug in tracts free from pollution. A fine white siliceous silver sand of fairly uniform grain is desirable, and this is sometimes prepared by screening. Coarse sand and fine gravel (known as 'hoggin') are also used in filter-beds.

The top layer is composed of fine sand from about 2 to 4 feet thick, with under-layers of fine and coarse gravel, and occasionally broken stone or rubble, the whole sometimes not more than 4 or 5 feet in depth. Filtration takes place at rates varying from 2 to 6 inches per hour. A slow process, combined with aeration and bacterial action, is desirable. It has been reckoned that from $2\frac{1}{2}$ to 4 million gallons of water can be filtered from an acre of filter-bed during the course of a day, or from 500 gallons per square yard of surface in the same period.

Water treated with ozone becomes purified, and electric processes and more rapid filtration by chemical agents have been sometimes introduced. Purification by means of chloride of lime has proved efficacious. (See also remarks, p. 269.)

In the Fifth Report of the Rivers Pollution Commission (vol. i., 1874), the pollution arising from mining operations and from metal manufactures was dealt with. It was remarked, in reference to mines, that the matters discharged into rivers by collieries and coal-washing, by iron and manganese mines, and by China-clay works, though often unsightly, were not directly injurious to the health of persons. Thus, although the coal-washings near Chesterfield had converted the Rother into a black river, they had not prevented the use of the Don for the water-supply of Doncaster, at a distance of about twenty miles below the junction of the two rivers. The matter in suspension, however, was a drawback locally to the use of the water for domestic purposes.

The waste-matters discharged from mines of lead, zinc, copper, arsenic, tin, and carbonate of baryta, were said to be 'frequently of a character to produce injury to the health of persons using the water for domestic purposes, or of cattle grazing in fields which have been flooded by water so fouled.' Many of these refuse matters were also destructive to fish.

It was, however, noted that, as the polluting matters are nearly always in suspension, and rarely in solution, so that the water appears muddy and repulsive, cases of injury to health of persons had rarely happened.

The most serious injury had been caused by the discharges of waste matter from lead-workings. The streams were rendered turbid with the mud or 'slimes,' and flood-waters then destroyed grass on the alluvial meadows and injured cattle. The refuse of tin and copper mines was stated to be but slightly poisonous, and the injury was chiefly that due to the loading of grasslands with mineral matter during floods.

CHAPTER XV

MINERAL WATERS

WHILE all underground waters contain a certain amount of mineral or saline matter in solution, it is only when the amount is excessive, or composed in part of some special substance, that the term 'mineral water' is applied. Within the limits of about 60 or 70 grains of mineral matter per gallon, there may be said to be a gradation from a potable water to one that is unsuitable for the purpose.

In many cases it is difficult to account for great divergences in the composition of water derived apparently from the same strata at no great distance apart. Concealed faults and dykes of igneous rock in some cases affect the underground circulation.

Water, strictly speaking, is a mineral; when pure it has a definite chemical composition, and in the form of snow, frost, and ice, it has definite crystalline forms in the hexagonal system.¹

It is present in all rocks as 'water of crystallization' or 'combined water,' chemically combined with salts; or in minute cavities in crystals; or in the interstitial spaces, in which form (as noted on p. 41) it is known as 'Quarry water.'

¹ See *Nature*, June 24, 1909, p. 492.

Mineral waters are usually classed as follows :

Saline.

Chalybeate.

Sulphurous or stinking wells.

Calcareous or petrifying springs.

The presence of sulphuretted hydrogen distinguishes the sulphurous waters, but the saline ingredients vary in amount in different waters, and there is often no special reason to distinguish saline from chalybeate waters. In many localities both saline and chalybeate springs occur. Other waters are specially designated from the occurrence, usually very small in amount, of lithia, iodine, bromine, or barium, which are present among other constituents.

Brine springs have a character of their own, and they are valuable from a medicinal as well as a purely commercial point of view.

The healing properties of some springs have long been known, and these medicinal waters are sometimes classified according to their therapeutic qualities—as aperient or purgative, with magnesium and sodium sulphates, sodium chloride and sodium carbonate ; or as thermo-chemical, thermo-mechanical, and thermo-electrical.

In Mineral waters the following constituents are among those more commonly present :¹

Aluminium sulphate	...	Harrogate.
Ammonium carbonate	...	Harrogate.
chloride	... ..	Harrogate.
Barium carbonate	...	Harrogate.
chloride	... ..	Harrogate, Llangammarch.
sulphate	... ..	Harrogate.

¹ The localities mentioned are examples among many where the particular ingredients occur.

Calcium carbonate	...	<i>In most waters.</i>
chloride	...	Ashby - de - la - Zouch, Builth, Harrogate, Leamington, Llan- drindod, Shap Wells, Wood- hall.
nitrate	...	Bath.
sulphate	...	Bath, Harrogate, Tunbridge Wells.
Ferrous carbonate	...	Bath, Harrogate, Moffat, Tun- bridge Wells.
chloride	...	Harrogate.
sulphate	...	Harrogate.
Lithium	...	Bath, Builth, Buxton, Harrogate, Matlock, Moffat.
Magnesium bromide	...	Harrogate.
carbonate	...	Bath, Harrogate.
chloride	...	Bath, Harrogate.
iodide	...	Harrogate.
sulphate	...	Cheltenham, Epsom, Harrogate.
Manganese chloride	...	Harrogate.
Potassium bromide	...	Woodhall.
carbonate	...	Harrogate, Tunbridge Wells.
chloride	...	Harrogate.
iodide	...	Woodhall.
nitrate	...	Bath.
sulphate	...	Bath, Cheltenham, Harrogate.
Rubidium	...	Bath.
Silica	...	Bath, Harrogate.
Sodium carbonate	...	Harrogate.
chloride	...	Ashby - de - la - Zouch, Bath, Builth, Cheltenham, Harro- gate, Leamington, Llandrin- dod, Llangammarch, Llan- wyrtyd, Shap Wells, Shearsby, Woodhall.

Sodium iodide	...	...	Harrogate.
nitrate	...	...	Harrogate.
silicate	...	...	Harrogate.
sulphate	...	...	Bath, Cheltenham, Leamington.
Strontium	...	...	Bath, Buxton, Matlock.

Considerable deposits are found in the mains that supply the hot waters of Bath to the several baths. The presence of radium in the Bath waters and deposits, and in deposits from the Buxton waters, has been determined by the Hon. R. J. Strutt.¹ The springs in the Trenwith Mine, St. Ives, have been found by Sir William Ramsay to exhibit remarkable radio-activity. Traces of copper have been noted in the Bath waters, and of lead in those of Buxton.

Of gases given off by mineral waters the following may be mentioned :

<i>Sulphuretted hydrogen</i>	...	...	Askern (near Doncaster), Harrogate, Lisdoonvarna (Co. Clare), Llandrindod, Llanwyrtyd, Moffat, Strathpeffer.
<i>Nitrogen</i>	...	...	Bath.
<i>Oxygen</i>	...	...	Bath, Harrogate.
<i>Carburetted hydrogen</i>	...	...	Harrogate.
<i>Carbonic acid</i>	...	...	Bath, Harrogate.

Carbonic acid gas, Nitrogen, and Oxygen, are present in most natural waters.

Oil-wells have occasionally been notified in this country, and have in several instances proved to be due to leakage from stores of Naphtha. Mr. Beeby Thompson called attention to one such instance at Husbands Bosworth in Leicestershire.²

¹ See *Nature*, March 17, 1904, p. 474.

² *Journ. Northamptonshire Nat. Hist. Soc.*, xiii., 1906, p. 267.

A 'burning well' was discovered in 1711 at Broseley, and this phenomenon, as noted by Mr. John Randall, was due to petroleum, which issued from the Coal-measures into a well, and was occasionally ignited. A petroleum spring has also been observed at Pitchford in Shropshire.

With regard to the origin of the mineral ingredients in waters, the following causes have contributed :

1. The decomposition of rocks, with their included minerals and fossils.

2. Rain conveying acids and sodium chloride in spray from the sea.

3. Manures on cultivated lands, from which calcium phosphate and sulphate, magnesium carbonate and sulphate, potassium silicate and sulphate, sodium chloride, nitrate and sulphate, may be derived; also sewage contamination in soil.

4. Infiltration of sea-water near coasts, and to some distance inland through fissures and along fault planes.

5. The original saturation with sea-water of marine strata, or of these and other strata which have been formed, and perhaps subsequently upraised and depressed, beneath the ocean. They are therefore said to hold 'fossil sea-water.'

6. The upward flow of water under artesian pressure, derived from a considerable depth, where increase of temperature is more potent in the decomposition of rock materials.

7. Deep-seated sources, where the subterranean heat, as in volcanic regions, may cause the outflow.

Mr. W. W. Fisher has published the results of analyses of saline waters from the Lower Greensand and Oolites in the Southern Midland counties of England, and has come to the conclusion that the

mineral constituents are derived from the strata. In some cases in the Lower Greensand the waters have travelled underground about three or four miles, percolating through the porous strata 'at an extremely slow rate, the conditions thus in the highest degree favouring the extraction of soluble matters.' In the Oolites, Mr. Fisher finds that the uncovered beds of limestone yield calcareous (hard) waters, while at a depth they frequently yield saline or alkaline supplies. In these cases he is of opinion that the mineral ingredients are derived from the strata, and they become more or less concentrated where the waters are pent up without natural outlet.¹

The view that the soluble salts of a series of deposits may represent the salts of the original or 'fossil' seawater of the area of deposit has been discussed by Dr. W. Mackie, who considers that the inference 'must in the majority of cases be a very uncertain one.'²

Water draining through the soil will remove a part of the soluble matter, such as calcium carbonate and the calcium and sodium nitrates, chlorides, and sulphates. Thus, according to Mr. R. Warington, 'The loss of nitrates from highly manured land during a wet season is very considerable, and will frequently be equal to several hundred pounds of nitrate of sodium per acre.'³ In the case of ammonium sulphate he has remarked that sulphuric and nitric acids unite with lime, and the calcium salts may be removed by drainage. Much, however, depends on the nature of the soil.

¹ *Analyst*, July, 1902 ; February, 1904.

² *Rep. Brit. Assoc.* for 1902, p. 559.

³ 'Chemistry of the Farm,' 4th revision, 1907, p. 42.

Shallow wells have had the temperature of their water raised by the oxidation of organic matter in the shape of farmyard manure ; instances have been noted in the Fen district near Chatteris.¹ Some increase of heat has also been attributed by J. H. Taunton (1887) to hydrostatic pressure, and the friction caused by water traversing strata. The influence of radium has also to be considered as well as that due to volcanic forces.

The Alkali soils met with in certain arid regions in the United States, India, and Egypt, are due to the presence of sodium chloride, together with sodium, magnesium, and calcium sulphates, and sometimes sodium carbonate, potassium and magnesium chlorides. Sodium carbonate is known as 'black alkali,' because, as remarked by Mr. J. D. Tinsley, it appears to blacken the vegetable matter in the soil ; other salts form the 'white alkali' soil. These salts are brought into the soil by capillary attraction from water holding the salts in solution, and on the drying of the surface an efflorescence or incrustation remains.² The salt-licks in the United States are examples.

Irrigation has been adopted in many cases, but, unless accompanied by underdraining at a deeper level than the irrigation channels, this process of washing the land is ineffective.

In Egypt, according to Mr. A. Lucas, the Ismailia Canal by seepage through porous soil has raised the general level of the subsoil water, and brought salts of soda, notably sodium carbonate, to the surface.

¹ O. Fisher, F. W. Harmer, *Geol. Mag.*, 1871, pp. 42, 143 ; Skertchly, 'Geol. Fenland,' *Mem. Geol. Survey*, 1877, p. 243.

² See A. D. Hall, 'The Soil,' 1903, p. 223.

Mr. H. B. Maufe has noted in several wells near Naivasha, in the East Africa Protectorate, that when first sunk the water was fresh, but in the course of some weeks it became too saline for use. The explanation was that higher water which had percolated through soil containing an excess of alkaline salts was drawn into the well to replace the water abstracted. The remedy was to line the upper part of the well.

Chalybeate Waters.—Springs and well-waters derived from ironstone strata are not necessarily charged with an injurious amount of iron-salt. They may contain only about 1·5 grains per gallon of ferrous carbonate. The chalybeate spring at Tunbridge Wells contains nearly 4 grains per gallon. It is usually the case with the rocks of the New Red Sandstone series, that the iron-oxide which coats the grains of sandstone is the insoluble peroxide.

Iron-ore held in solution is deposited when exposed to oxidizing agencies by exposure to the air, and by organic action. Hence we find the name of Red Wells or Scarlet Wells, Rodwell, Rothwell, etc. What is called iron-pan, a hard sandstone or conglomerate cemented by impure limonite, is sometimes formed at the base of sand and gravel, where the water is upheld by an impervious layer.

Calcareous or Petrifying Springs.—These are of common occurrence in limestone districts. The Dropping Well at Knaresborough issues from a crag of Magnesian Limestone; the so-called ‘petrifying spring’ of Matlock from the Carboniferous Limestone, and those of Dursley and Chalford, near Stroud, from the Inferior Oolite.

Saline Waters have been encountered in a number of deep wells, and in different geological formations. The more noted cases have occurred beneath the New Red Marls, where water in the underlying Red Sandstones has become impregnated with saline springs from the salt-bearing Red Marls.

In some cases in Worcestershire and Gloucestershire saline waters issue from Liassic strata, which may derive their ingredients along fault-planes from saliferous strata below.

Salt-water, derived probably from Triassic rocks, was found in deep borings at Kingsthorpe and Northampton, as well as at Rugby and Lincoln, as elsewhere noted ; and pumping may afford no remedy when the saliferous strata are the cause.

In other cases, where the water has been long undisturbed by having no natural outlet, pumping may gradually reduce the amount of the saline ingredients, fresh-water being introduced at the outcrop to replace that withdrawn.

Attention has been drawn to the occurrence in Cape Colony of natural Salt-pans near the coast, and also in many places far inland. Those on the coast are separated from the sea by hillocks of blown sand, and are due to the rain-water, which derives salt directly from the sea-spray, or indirectly through the sandy deposits bordering the pans. These have an impervious floor, so that the water does not drain away, but evaporates, leaving a crust of salts.

The inland pans are circular or oval, and from one to four miles wide, with clayey base. Excavated by wind-action, these depressions receive from the rainfall and subsurface drainage saline ingredients, chiefly sodium

chloride, which appear as white incrustations after evaporation of the water in dry seasons. It is noted 'that very often round the edge of a salt-pan, or occasionally even within it, fresh-water can be obtained on digging shallow pits.'¹ (See also p. 249.)

In Western Queensland borings have encountered brackish water above sea-level, and fresh-water at a lower level.

At Swindon new town, at the Great Western Railway works, very saline water having a temperature of 64° F. was encountered at a depth of 730 to 736 feet in the Great Oolite Series. The total saline ingredients amounted to 2,131·85 grains per gallon, of which 1,824·37 were sodium chloride. The water was obtained in a shaft the site of which is marked W in Fig. 43. In this diagram A represents the Great Oolite; B, Forest Marble; C, Cornbrash; D, Oxford Clay; E, Corallian; G, Kimeridge Clay; H, Portland Beds; I, Purbeck Beds; J, Lower Greensand; K, Gault; L, Upper Greensand; and M, Chalk. The Oxford Clay and lower strata are represented as resting on an irregular mass of older rocks, P.

At a higher level in the Corallian strata, saline waters having 144 grains per gallon (86 being sodium chloride) were met with in the same shaft at depths between 72 and 112 feet.

Here we have an instance of water forced up by artesian pressure along joint-planes, and probably along a fault into higher strata, where the more saline water is diluted.

In such cases the salinity of the lower waters is not likely to be lessened by pumping.

¹ 'Geology of Cape Colony,' 2nd edit., by A. W. Rogers and A. L. Du Toit, 1909, pp. 411, 415, 416.

Nowhere beneath the surface in Wiltshire has the floor of Palæozoic rocks been reached by well or boring. It is, however, well known both on the west and east, in the Mendip area and in the London district, that Jurassic rocks rest on an irregular floor of the older rocks, and it is by no means improbable that this is the case below Swindon and the country to the south. Thus, much saline water may be derived from Carboniferous Limestone, Coal-measure Sandstones, or other old rocks, and introduced amongst the overlying strata, as suggested by the diagram.

Several lines of fault running generally in a north-easterly direction between Frome and Swindon are marked on the Geological Survey Map, and it is possible that some saline waters burst out along these lines of dislocation. We can understand the introduction of saline waters from below into the Great Oolite series, if the Lower Jurassic clays be absent or overlapped; but their occurrence in the Corallian series, having regard to the intervening mass of Oxford Clay, is puzzling. It may, however, be explained by the uprise of saline water along the margin of older rocks, and with some influx of fresh-water from the surface along the fault-plane F, as represented (hypothetically) in Fig. 43.

Saline waters have been met with in many parts of Wiltshire, as at Melksham, Purton, etc., also at St. Clement's, Oxford; and they have been encountered in borings beneath the Oxford Clay, at King Stag in the Vale of Blackmore in Dorset, and at St. Neots in Huntingdonshire.

Saline waters have been encountered in the Oolites and Lias below the Oxford Clay in the neighbourhood

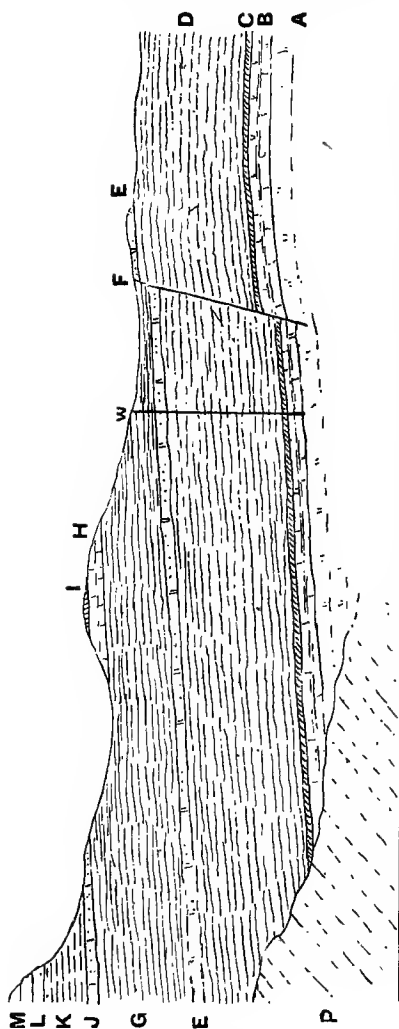


FIG. 43.—DIAGRAM TO EXPLAIN THE OCCURRENCE OF SALINE WATERS AT SWINDON.

of Oxford, as at Kidlington, at a depth of 467 feet ; at St. Clement's, Oxford, at a depth of 280 feet ; and in a

boring at the City Brewery, Oxford, made in 1898 by Messrs. Le Grand and Sutcliff. The strata passed through in this last boring were as follows :

	Thickness in Feet.
Valley Gravel, etc.	30
Oxford Clay	210
Cornbrash	17
Forest Marble	32 $\frac{2}{3}$
Great Oolite	88
Upper Estuarine Series	28 $\frac{1}{2}$
Inferior Oolite	16 $\frac{1}{8}$
Lower Lias	17
Total depth	439 $\frac{1}{2}$

It was not proved whether the Inferior Oolite rested unconformably on the Lower Lias by overstep, or whether the two formations were faulted together.

A feeble supply of water, which rose to the surface, was obtained from a depth of about 402 feet, apparently from the basal part of the Estuarine Series, but derived probably from the Inferior Oolite. It proved to be highly saline, the analysis by Mr. W. W. Fisher being as follows :¹

	Grains per Gallon.
Sodium chloride	286·0
Sodium sulphate	323·9
Magnesium sulphate	18·0
Calcium sulphate	11·42
Calcium carbonate	28·0
Silica and iron oxide	1·19
	668·51

¹ See 'Geology of Oxford,' *Mem. Geol. Survey*, 1908, p. 123.

It is noteworthy that, in a number of localities, saline waters, containing much sodium chloride, have been encountered in the Coal-measures, and in situations where the ingredients could not have been derived from adjacent salt-bearing New Red rocks. Such is the case at Radstock and Twerton, in Somerset, at Ashby - de - la - Zouch, in Leicestershire, in various localities in the North of England, in Flintshire, and at Llangammarch and Llandrindod.

The occurrence of Brine springs is due, in many cases, to the presence of beds of rock-salt in the New Red rocks from which they issue. This is the case in the principal wells that are utilized for medicinal purposes, as at Droitwich and Nantwich.

For commercial purposes, as in Durham and the North Riding of Yorkshire, water derived from overlying red sandstones is introduced into the lower saliferous strata, whereby salt is dissolved and removed by pumping the brine. About 3 pounds of salt per gallon can be removed by brine-pumping.¹

The removal of the rock-salt in the North-eastern counties has not been attended with the disastrous subsidences that have occurred in some parts of Cheshire. In certain cases, where the salt had been mined, the subsequent inflow of water has dissolved the salt pillars that were left to support the roof of the workings.

In wells or borings made near the sea-coast, as at Clacton-on-Sea, Southwold, Hornsea, and at Sunk Island, on the Yorkshire side of the Humber, brackish or saline waters have been encountered.

Wells in the Chalk at Eastbourne and Newhaven have been affected by the influx of sea-water, and this

¹ *Nature*, March 28, 1901.

has been the case also with some wells at Bristol, Plymouth, and Dublin, where the water has proved to be brackish.

Well-waters are sometimes found to be saline on the borders of the lower Thames, where the Chalk lies beneath the Alluvial deposits and also appears at the surface, as between Erith and Gravesend, at Purfleet and Grays. Dr. J. C. Thresh (1901) has drawn attention to the waters encountered at Purfleet in three wells in the Chalk; in one the water from the first 200 feet was salt, whereas fresh-water was met with lower down. In two other wells near by good water was obtained from depths of 112 feet and 130 feet respectively.

Wells at Grays and Barking carried into Chalk have been affected by the Thames water, on account of the large supplies that have been pumped.

The fact is that the scour of the tide, as remarked by Mr. Clayton Beadle (1908), prevents the permeable beds, over which a large part of the lower Thames flows, from being pugged by the deposition of river mud.

Isaac Roberts (1878) made experiments on the filtration of sea-water through the Triassic sandstone (Bunter sandstone and pebble-beds) of Liverpool. At that date several million gallons of water were daily pumped in the city within a mile of the Mersey, and the water had been found to become more brackish year by year. Experiments showed that in filtration nearly the whole of the salts (80·8 per cent. of the chlorides) were removed, and mechanically held in the sandstone; but by subsequent operations less and less of the saline matters were held.

C. E. De Rance remarked (1896) that at Bootle, near Liverpool, there is a north and south fault parallel with the coast, and that on the west the tidal waters of the Mersey infiltrate, whereas on the eastern side of the fault the well-water is fresh.

Fig. 44 represents in diagrammatic form the kind of structure which would cause the difference. A may represent sandstones or limestones; B, Shales; C, the water-bearing beds that are displaced by the fault F, and are liable to the influx of sea-water on the left or upthrow side. The shales and marls, D, prevent the infiltration of saline water into the strata C, on the downthrow side of the fault.

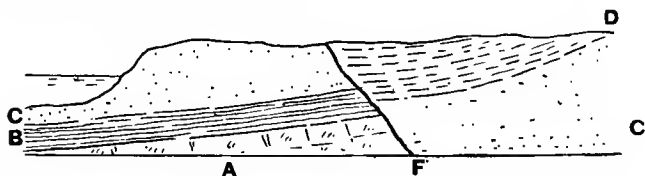


FIG. 44.—DIAGRAM TO EXPLAIN THE INFILTRATION OF SEA-WATER IN PROXIMITY TO STRATA YIELDING FRESH-WATER.

Experiments recorded by Mr. Baldwin-Wiseman (1907) on the flow of strong brine through Bath oolite (weatherstone) showed that at first the effluent was cleared of all the salt in solution. Subsequently with a weaker brine the effluent became stronger than the inflowing solution, deriving salt from the pores of the rock.

J. A. Phillips observed that, while the slates of Botallack in Cornwall are highly magnesian, the sea-water which percolates through them into the workings of the mine has lost three-fourths of its magnesium.¹

¹ *Quart. Journ. Geol. Soc.*, xxxi., 1875, p. 324.

Temperature of Waters.—The normal temperature of springs in this country varies from about 47° to 51° F., but it is subject to variation in different situations and countries. Both springs and deep well-water are usually cooler than the atmosphere in summer, and warmer in winter.

In the tropics the seasonal variations extend but a few feet below ground, and in temperate regions to about 50 feet. The precise amount is difficult to determine. The increase of temperature below, usually reckoned at about 1° for every 55 to 60 feet, is subject to considerable differences in some localities, ranging, in fact, from 1° in 20 feet to 1° in 130 feet.

In the boring at Grenelle, 102 feet above sea-level, carried to a depth of 1,800 feet, the temperature was nearly 82° F.; at Huel Clifford, Gwennap, Cornwall, at a depth of 1,320 feet below sea-level, the temperature of the water was 125° .

Thermal Waters rise from a depth probably greater than that indicated by their temperature, when they occur in non-volcanic regions. They issue along planes of dislocation or faults, which may be more pronounced at a depth if the disturbances took place mainly before the strata at the surface were laid down. Such an explanation may account in some cases for the issue of thermal waters in proximity to those of normal temperature. (See p. 292.)

Of the warm springs which occur in England and Wales, the temperature is as follows: Bakewell, 60° F.; Taff's Well, Cardiff, 65° ; Stoney Middleton, 65° ; Matlock Bath, up to 68° ; Clifton, Bristol, 70° to 76° ; and Buxton, 82° .

The hot springs of Bath have a temperature of 104°

to 120°, and are derived from three springs, known as the King's Bath, Hot Spring, and Cross Bath Spring. The united yield is estimated at about half a million gallons daily, and the records indicate that there has been no diminution in the temperature, nor in the quantity, except where due to leakage. The waters were considered by Prestwich to rise from a depth of about 3,500 feet, probably from a basin of Carboniferous Limestone underlain by Lower Limestone Shales.

In Idaho the Mountain Home hot springs have a temperature ranging from 103° to 167°, and in that region, according to Mr. I. C. Russell (1892), the temperature gradient is 1° for every 45 feet, below the stratum of no seasonal variation. The springs, might in his opinion, be increased by drill-holes, as fissure-springs rising through alternations of porous and impervious rocks are liable to lose much in bulk. He remarks: 'The depth to which it would be justifiable to continue drilling in the case of the Mountain Home hot springs, as indicated by their temperature, is about 5,000 feet. . . . There is, however, a chance that an open fissure that will yield an abundant supply will be struck at less depth.'

In Australia, the Mound Springs, near Hergott, according to Professor J. W. Gregory (1906), rise through fissures from bordering old rocks, and from a great depth. They are hot and saline, and deposit mineral matter in mounds around their outlets.

Geysers, or boiling springs, occur in regions of former volcanic activity. Their outbursts are intermittent, and are attributed to the descent of groundwater to highly heated or molten rock.

In their earlier stages, steam and boiling water are thrown up from fissures at intervals, and to great heights (200 feet or more). In time the penetration of cool water so diminishes the heat that steam is no longer erupted, and only hot springs issue more or less spasmodically. Geysers thus appear to represent the declining stages of volcanic eruptions.

In Iceland and in the Yellowstone Park, many geysers continue in the more active condition.

In New Zealand the outbursts of steam no longer occur, but there is every gradation from boiling springs to warm and bubbling pools.¹ Even in the Yellowstone Park, 'where there are said to be something like 3,000 vents of all sorts, hot springs which are not eruptive greatly outnumber the geysers. Of these latter, more than sixty exist.'²

In these cases we have surface-waters descending to locally heated horizons at a considerable depth beneath the surface, whence they ascend charged more or less with siliceous and other mineral matter.

Deep-seated and Surface Waters and the Saltiness of the Sea.—Other thermal waters or hot springs may arise from great depths, along planes of fault and fracture or along the junction of different formations.

As already noted, Professor J. W. Gregory (1906) has suggested that a good deal of artesian water in Australia may be derived from molten igneous sources, sometimes termed plutonic, magmatic, and hypogene. This is a speculation that has not received support from geologists in that country, and can at present be

¹ J. Malcolm Maclaren, *Geol. Mag.*, 1906, p. 511.

² Chamberlin and Salisbury, 'Geology,' i., p. 224, etc.

only regarded as a possible source of increase to some deep-seated waters.

Suess has remarked on the two kinds of waters that may be distinguished: 'The *vadose* waters—a name originally chosen by Pošepny for the waters which infiltrate from the surface, and escape from mineral lodes—include all the waters of the earth's surface, such as oceans, rivers, clouds, atmospheric precipitations, and artesian springs.¹ *Juvenile* waters, on the other hand, are those which arise when the hydrogen issuing from the earth's interior, under very high pressure and at a very high temperature, combines with the oxygen of the atmosphere. The white balls of steam emitted by the volcano become clouds, and a juvenile rain pours down its slopes. The juvenile hot springs bring up unexpected mineral matters from the depths . . . Thus, with every volcanic eruption the quantity of vadose water present on the earth's surface is increased. The atmosphere also is continuously enriched. While formerly the Ocean was supposed to be the source from which, by infiltration, the volcanoes are supplied, now it is regarded as the receptacle for juvenile waters; the quantities of chlorine which it contains are consistent with this view.'²

Dr. A. Harker has remarked on the probability that 'the small local reservoirs of individual volcanoes are not necessarily situated at any very great depths below the surface,' and he mentions estimates of from 1,000 to 3,000 metres. The parent magma-basins, however, must occur at very considerable depth, and although

¹ Sometimes termed 'meteoric waters.'

² 'The Face of the Earth.' English translation by H. B. C. Sollas, vol. iv., 1909, p. 548.

there are no data to determine the amounts, they may be 'measured probably by decades of miles.'¹

With regard to the water which issues from great depths in volcanic eruptions, he is disposed to regard it as original or magmatic, and not derived from oceanic or other surface sources. Thus, as he observes, 'Water and various gases are present in all igneous rocks, even the most deep-seated, which have been examined. The water amounts on the average to about $1\frac{1}{2}$ per cent., a proportion quite sufficient to endow the molten rock with the properties displayed in volcanic eruptions.' Therefore, 'it would seem, not that the sea is the source of the volcanic water, but that vulcanicity (in the broad sense of direct communication between the heated interior and the exterior of the globe) is the original source of the oceanic waters, and is slowly adding to them.'

Most authorities agree that the saltiness of the sea was original, though subject to modification by various agencies, now and throughout the geological periods. In the course of time much material has been derived from it by organisms, and stored up in the strata, the subsequent waste of which, by rain, rivers, and sea, is continually returning saline ingredients. Rock-salt is brought from saliferous New Red rocks, and from the decomposition of sundry crystalline and sedimentary rocks, so that there has been a constant interchange of material from sea to land and *vice versa*.²

Prestwich mentioned, on the authority of Fouqué, that in one eruption of Etna 5 million gallons of water

¹ 'Natural History of Igneous Rocks,' 1909, pp. 36, 38, 46, 48; see also E. A. Martel, 'L'Évolution Souterraine,' 1908, noticed in *Nature*, May 7, 1908, p. 2.

² See also Address to Geol. Soc., by W. J. Sollas, 1909.

were estimated to have escaped (as steam) in twenty-four hours. There seems little doubt that much land-water had accumulated in the porous and fissured volcanic materials in and around the eruptive centre during dormant periods, and this, as remarked by Fouqué, would gain access during the eruptions to some of the volcanic ducts. (See p. 129.) The loss of land-water would in certain cases be replaced by an influx of sea-water, and this 'agrees with the fact that diatomaceous fresh-water remains are common in many eruptions, and marine remains in others.'¹ Such water, however, was not necessarily the cause, but a result of the volcanic phenomena.

The question of the lowest theoretical limit at which underground waters may exist in the earth's crust has been discussed by Mr. C. S. Slichter (1902). The limit is reckoned to be about six miles, as below that depth the pressure would prevent the presence of any pores, cracks, and cavities, in the rocks. Others would restrict the limit of the 'zone of fracture' to a lesser depth of about 10,000 feet,² but, as free circulation of water diminishes as a rule with depth, it is safer to reckon that ordinary supplies of water should be looked for within a depth of about 2,000 feet.

¹ Prestwich, *Proc. Roy. Soc.*, 1885, pp. 256, 257.

² See 'Geology,' by T. C. Chamberlin and R. D. Salisbury, vol. i., 1905, p. 205, etc.

CHAPTER XVI

CONCLUSION

THE desirability of a National Water Board, or Department of Water Conservancy, has been advocated for the past thirty years, and more recently by Professor Sims Woodhead (1905), who has remarked on the somewhat limited powers of the present River Boards, and has urged that a National Water Board should act as arbitrators, and in conjunction with County or District Committees.

The Metropolitan Water Board in 1907 agreed that it was desirable to urge upon Parliament the necessity for regulating the appropriation of water-supplying areas, so that the needs of the Metropolis as well as of other populous places might receive due consideration.

The increasing competition among Urban authorities for upland reservoir sites, as pointed out by Mr. Baldwin-Wiseman (1909), accentuates the need for a central authority that should study in detail the water resources, and control the distribution of it.

The needs of certain Midland and Northern towns have been considered in connection with the Derwent Valley water scheme, but other districts require to be portioned out with due regard to the general interests of the population.

Reference has already been made (p. 100) to the want of definite and systematic information relating to the flow of many of our rivers.

In 1878 a Public Congress on National Water-Supply was summoned by the Society of Arts, at the suggestion of King Edward VII. (then Prince of Wales), who was President of the Society, the object being to discuss 'how far the great natural resources of the kingdom might, by some large and comprehensive scheme of a national character, adapted to the varying specialities and wants of districts, be turned to account, for the benefit, not merely of a few large centres of population, but for the advantage of the general body of the nation at large.'¹

During the Congress, Mr. J. Bailey Denton expressed himself 'perfectly convinced that, if there existed (1) a proper conservancy of rivers extending over the whole area of their basins, (2) an exact knowledge of the hydro-geological conditions of each river-basin, and (3) legal facilities for dealing with the water rising up within, and flowing through, and existing under, private properties, there would not be a single village in the country but might be abundantly supplied with pure water.'

Regulations are required concerning the use of any portions of a river system. The watersheds and gathering grounds in general should be protected from sources of pollution, and the higher courses of streams and rivers should be likewise guarded. As before remarked, the boundaries of river-basins are in places so

¹ On this subject, see also 'Conference on Water-Supplies and River Pollution,' *Journ. Sanit. Inst.*, xxii. ; also Reports of the several Royal Commissions on Water-Supply, River Pollution, and Sewage Disposal.

very uncertain that it would be necessary to fix some definite, if artificial, limits.

Some rivers are grossly contaminated, and it is a matter for consideration whether, as noted by Mr. M. O. Leighton (1903), 'there are waters which are more valuable as a disposal area for manufacturing refuse than they would be if maintained unpolluted.' The personal element naturally comes in when the Duke of Sutherland remarks (*Standard*, July 24, 1905) that Trentham Hall was becoming uninhabitable because of the amount of sewage pollution thrown into the Trent by the communities in the Potteries. The question, however, is one affecting the public generally, and Dr. W. N. Shaw, in discussing the subject of streams, suggested 'the alternative of making a special channel to carry away pollution,'¹ so that the natural watercourses might be more generally used for domestic purposes.

Control should be exercised over all sources of water-supply, and, as Mr. C. Beadle (1908) advocates, 'only such water should be taken as can be taken in perpetuity without affecting already established interests.' It is necessary, as he observes, to distinguish between supplies obtainable and supplies available.

Thus, some geological formations, like the Chalk, have acted as natural reservoirs during a long course of years, and excessive pumping removes more than can be replaced by the annual rainfall. The flow of springs and streams is thereby diminished.

Running water cannot be taken without compensation, but underground water may be drawn upon without restriction, although the water beneath neigh-

¹ *Journ. Statist. Soc.*, lxxii., 1909, p. 296.

bouring ground may be depleted or seriously lessened. There is no redress for the depletion of a spring or of a neighbour's well, unless it can be proved that the underground water that is drawn upon flows in a defined channel; or unless the undertaking is a large one requiring Parliamentary sanction, or the approval of the Local Government Board, when it is possible that compensation clauses can be inserted in the agreement, to provide against interference with other local sources of water-supply.¹ In Colorado the water is the property of the State.

Uniformity in the administration of water resources is evidently needed in Britain, so that the various independent authorities dealing with the Conservancy of Rivers, with Canals, Drainage, Sanitary matters, and Water-supply, could act to some extent in concert.

¹. In reference to legal questions and recent enactments concerning underground water, see J. S. Will, *Trans. Surveyors' Inst.*, xxxii., 1900, p. 255; W. V. Graham and H. F. Bidder, *ibid.*, xxxix., 1907; 'The Law relating to Waters, Sea, Tidal, and Inland,' by H. J. W. Coulson and U. A. Forbes, 2nd edit., 1902; 'Encyclopædia of the Laws of England,' xiv., 1909.

APPENDIX I

GLOSSARY OF SOME TERMS USED IN REFERENCE TO WATER AND WATERWORKS

N.B.—The definitions marked 'D.' are taken from the New English Dictionary those marked 'B. A.' are from the Report of a Committee of the British Association, 1907-08 (of which the writer was a member, and Mr. W. G. Fearnside, Secretary).

Adit. A level in a well-shaft, mine, or other underground working. Applied especially to a level used to drain the water from a mine when the configuration of the ground is favourable.

Aqueduct. An artificial water-way, channel, or conduit. Generally applied to open cuts or tunnels, as distinct from pipes.

Beck. A small stream.

Bourne. The headwaters of a river flowing from one or more large springs (Cambridge and East Anglia).—B. A. Applied also to the rising of a stream at a higher part of a valley after prolonged rain. (See p. 73.)

Broad. A lake or sheet of water bordering or forming the direct course of a sluggish river. Applied especially to the expanses of water along the courses of the Bure and Yare in Norfolk, and the Waveney in Suffolk. These are thirty in number, and the aggregate area amounts to 2,816 acres. (See R. B. Grantham, *Quart. Journ. Geol. Soc.*, xxv., 1869, p. 258.)

Burn. A brook or river (Scotland).

Catch-Meadows. Meadows irrigated by water from a hillside; water-meadows.

Chine. A short and deep ravine with watercourse cutting through cliffs and giving access to the shore (Hampshire and Isle of Wight).

Conduit. A water-way. Applied to covered and uncovered aqueducts and pipes.

Creek. Applied to water-channels in arid regions that are subject to periods of drought, and of sudden torrential flow of streams from mountain regions.

Drift. A subterranean gallery, adit, tunnel, or heading. Applied also to superficial deposits of boulder clay, gravel, etc.

Dub. A small pool; a reach of a small stream wherein still waters run deep (Lake District).—B. A.

Ea. Water. Applied to watercourses in the Fenland, as Popham's Ea.

Eosin. A brownish-red dye used for testing the direction of flow of underground water.

Fleet. A brook or river.

Fluorescein (chemical composition, $C_{20}H_{12}O_6$) is one of the triphenylmethane colouring matters, and is used for testing the flow of underground waters. 'Pure fluorescein is a brick-red crystalline powder, quite insoluble in water, sparingly so in the majority of other solvents. In caustic alkalies and in ammonia it dissolves with a brown colour. The solutions have, especially when dilute, a most brilliant and beautiful green fluorescence; hence the name of the substance.' (Dr. O. N. Witt in T. E. Thorpe's 'Dict. of Applied Chem.,' iii., 1893, p. 881.)

Flush. A state of flood during which the river does not quite overflow its banks (North England).—B. A.

Force. A waterfall (North England and Scotland).

Fountain. Applied sometimes to a spring, sometimes to a jet of water that rises naturally or artificially under hydraulic pressure. The 'fountain-head' is the source of an artesian or other supply of water in the outcrop of pervious or fissured strata.

Gill (misspelt 'Ghyll'). A steep and narrow ravine with stream in bottom; usually rocky, and with stream almost a cascade or waterfall (Lake District).—B. A.

Grains. The different branches of the headwaters of a burn (North England, South Scotland).—B. A.

Gulch. A dry bed or ravine occupied at times by a torrential stream.

Gutters. Rain-channels on mountain or hill slopes.

Hydrant. Apparatus for drawing water from a main.

Hydraulics. The science of the conveyance of water through pipes, and other artificial channels or aqueducts.—D.

Hydrodynamics (includes Hydrostatics). The science of forces acting upon, or exerted by, liquids.—D.

Hydrogeology. Geology in reference to water on or below the surface of the earth.—D.

Hydrography. Descriptive of waters on the earth's surface: currents, contours of areas covered by water, etc., and applied to marine and other surveys of areas of water.

Hydrology. The science of water; treating of water: its properties and laws, its distribution over the earth's surface, etc.—D.

Hydromechanics. The mechanics of liquids; the application of water to mechanical contrivances.—D.

Hydrophore. Instrument for procuring samples of water from a depth.—D.

Hydrosphere. Applied to that portion of the earth's surface which is covered by water, and reckoned to be about 72 per cent., the lithosphere, or stony surface, being about 28 per cent.

Hydrostatics. The science of forces or pressure exerted by liquids at rest.—D.

Hydrotherapeutics. Relates to water-cures.

Hydrothermal. In geology relates to the action of heated water on rocks, in dissolving mineral matters, and in producing metamorphism.

Hydrotimeter. Apparatus for testing the hardness of water by means of a standard soap-solution.—D.

Hyetograph. A recording rain-gauge made by Messrs. Negretti and Zambra (*Nature*, August 19, 1909, p. 227).

Hygology. The science relating to the humidity of the atmosphere, etc.

Hygrometer. Apparatus for measuring the amount of moisture in the atmosphere.

Hygroscopic. Applied to the amount of humidity in the air, and to the moisture absorbed from the atmosphere by soil, and retained on surfaces of constituent particles. The hygroscope is an instrument which indicates, without accurately measuring, the humidity of air.—D.

Isohyetal Lines. Lines of equal rainfall indicated on a map.

Kell. A spring or natural well.

Keld. A well or deep opening among rocks (Lake District).—B. A.

Kettle (or Giant's Kettle). A deep pot-hole excavated mechanically by streams aided by sand and boulders ; sometimes termed a 'cauldron.' Kettle-holes are irregular ponds or hollows among boulder clay or morainic matter determined by irregular deposition of the drift.—B. A. Hell Kettle is a name sometimes applied to wells, as at Oxenhall, Durham.

Leat. An artificial watercourse following the contour along the side of a valley (South-West England).—B. A.

Levadas. Artificial watercourses (Madeira).

Level. A horizontal working gallery, drift, or tunnel, in well-shaft or mine.

Limnology. The study of lakes.

Lin (Linn). A deep pool ; the reach of a river ; sometimes also a waterfall (South Scotland).—B. A.

Loat. A watercourse.—B. A.

Lochan. A small loch or lake.

Lode. A watercourse, usually partly artificial, and banked up above the surrounding country (Cambridge and East Anglia, especially in Fenland).—B. A.

Mell. A shallow lake (Lake District).—B. A.

Mere. A deep pond or shallow lake, frequently among glacial drifts. An incompletely filled marsh or pen in the process of silting up (England).—B. A. (See also p. 111.)

Ordnance Datum. Mean half-tide level at Liverpool. Zero is 20 feet below Ordnance Datum.

Pan. A depression into which rain falls and water drains (South Africa). Applied also to layers of sand and gravel hardened by ferruginous matter.

Pants. Applied to pools or reservoirs fed by springs (Northumberland).

Piezometer. Apparatus for testing the pressure of artesian water.

Pill. A little stream. Applied in Gloucestershire to streams draining the alluvial flats on the borders of the Severn Estuary.

Polarite. An iron carbide used for filtration purposes.

Potamology. The study of rivers.

Pow. A sluggish rivulet (Lake District).—B. A.

Pulk-Hole. Small ponds or pools of water (Norfolk).—B. A.

Ram (or Hydraulic Ram). An automatic pump in which the kinetic energy of a descending column of water in a pipe is used to raise some of the water to a height above that of its original source.—D. A stream may require to be dammed to produce the necessary fall or quantity of water.

Rhine. Applied to ditches and watercourses constructed for draining the marshlands of Somerset.

Shak (or Shakehole). A swallow-hole formed close under the shales which overlie the Carboniferous limestone; a large and deep form of swallow-hole (Pennine District).—B. A.

Sike (Syke). A small and marshy hollow through which a stream runs in wet weather; sometimes applied to the stream itself (Northumbria and Lake District).—B. A.

Sock. Wet portions of a field.

Sour-Milk Gill. A special type of gill in which banks become almost non-existent, and water cascades over a wide spread of bare rock. The name applies to the foaming waters which course down the unnotched side of a valley from the hanging valleys above (Lake District).—B. A.

Spate. A stream rendered torrential by heavy rain (Scotland).

Strid. A narrow portion of a river-course through which the waters flow with great turmoil (West Yorkshire).—B. A.

Tamp. To render water-tight a rocky or porous surface with clay, as in the construction of a pond.

Tarn. A small lake among the mountains, usually of glacial origin (West Britain).—B. A.

Thwaite. A watery place.

Tite. An obsolete word applied chiefly in Oxfordshire to springs of water. There is a copious spring from the base of the Inferior Oolite at Tite End, Chipping Norton. (See Hudleston, *Proc. Geol. Assoc.*, v. 383).

Trinity High-Water Mark. 12 feet 6 inches above Ordnance Datum.

Turbine. Applied to a water-wheel with horizontal action.

Wall-ee. A spring covered over with a coating of spongy green moss or other bog vegetation (West Yorkshire and Scotland).—B. A.

Water-Race. A channel for conveying water to mining-works.

Waterspout. A gyrating column of mainly rain-water, due to a whirlwind on sea or fresh-water or land ; advancing sometimes from sea overland or *vice versa*. Those encountered on sea may be slightly brackish. In a Naval Dictionary (1804) it is stated that, when a waterspout is observed at sea, 'it is usual to fire cannon at them to break them.' (See reference to Cloud-Burst, p. 10.)

Water-Way. Applied to canals, aqueducts, lakes, streams, and navigable rivers.

Whirlpool. An eddy of water caused by opposing currents and irregularities of the bed of the sea or stream.

APPENDIX II

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